INPUT PARAMETER UPDATES TO THE MACCS COMIDA2 MODEL

Prepared for

U.S. Nuclear Regulatory Commission
Contract No. 31310018D0002
Task Order No. 31310018F0093

Prepared by

Osvaldo Pensado and Daniel Speaker

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

May 2020

EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) sponsored development of the MELCOR Accident Consequence Code System (MACCS) code to assess offsite consequences from an atmospheric release of radioactive material from a hypothetical nuclear power plant accident (Chanin et al., 1998). MACCS, with its Windows-based graphical user interface WinMACCS (McFadden et al., 2007), is used to assess severe accident consequences, assist in emergency planning for nuclear sites, and support severe accident mitigation alternatives (SAMA) evaluations (NRC, 2018).

COMIDA2 is a food-chain model used by MACCS to estimate dose-to-source ratios from ingestion of contaminated foodstuffs. The COMIDA2 output allows MACCS to project temporal interdiction of agricultural products for consumption, and to estimate cumulative radiological population doses for agricultural areas that are not subject to interdiction. Recommended input parameters for the COMIDA2 code have not been systematically reviewed since the publication of the code manual NUREG/CR–6613 in 1998 (Chanin et al., 1998, Volume 2) nor have those inputs been incorporated in example input files distributed with MACCS. The objective of this report is to evaluate input parameters and compile tables with updated values, especially in light of more recent radioecological modeling efforts and data compilations, such as the Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments (IAEA, 2010). An additional objective was to clarify the meaning of input values and document relevant COMIDA2 assumptions and approximations to the selection of those input values, to guide future updates.

In general, NUREG/CR–6613 (Chanin et al., 1998, Volume 2) recommended default values for the majority of the parameters. For most of the parameters, more recent references and information than cited in NUREG/CR–6613 are available to support updates. Tables with updated input values compiled during this project are included in this report. Substantial effort was aimed at understanding the meaning of the multiple inputs to the COMIDA2 model, supported by sensitivity analyses, and documenting model approximations and interdependencies that influence selection of input values, beyond information in the existing model documents (e.g., Chanin et al., 1998, Volume 2; Abbott and Rood, 1993, 1994). The COMIDA2 model accounts for effective parameters that represent multiple processes or aggregated inputs; thus, relying on averages, bounding input values, and judgment is unavoidable. The rationales for the selection of input values and original sources are documented in this report. Because of the COMIDA2 model approximations, it is concluded that generic inputs are appropriate for most analyses. Only a few inputs may need to be selected based on site-specific information, such as food consumption rates and production rates. Developing precise site-specific information for these inputs is very labor intensive, requiring surveys to establish average diets and the amount of food that is locally produced and consumed. However, an approach to define production rates based on a national census, the extent of farm areas, and the fraction of the food production for national consumption (e.g., Chanin et al., 1998, Volume 2, Section 2.2.2), is a sound approach for general estimates of consequences. Most of the site-specificity is captured by the magnitude of the fallout event, the number of people affected, and the size of the affected area, all of which are inputs outside of the COMIDA2 food-chain model.

Sensitivity runs were executed varying one-parameter-at-a-time, using a baseline case. The baseline case included constant COMIDA2 inputs with all of the updated inputs identified in this report. The majority of the original inputs that based on NUREG/CR–6613 (Chanin et al., 1998, Volume 2) were updated based on more recent information (e.g., International Atomic Energy

Agency and US Department of Energy compilations). Parameters were varied, when possible, over two orders of magnitude (centered around the baseline updated inputs) for the sensitivity analysis, often beyond the range of physical variability, with the goal of examining the mathematical structure of the COMIDA2 model around the baseline case. The main goal of the sensitivity analysis was to complement the COMIDA2 documentation on the meaning and effect of input parameters, and COMIDA2 model assumptions and approximations affecting the selection of inputs values, to facilitate further updates to those inputs. The sensitivity analysis also served to identify parameters influential to the population dose and economic cost, with the caveat that parameter relevance conclusions depend on the baseline inputs (i.e., changing the reference case may change the sensitivity conclusions) and the domain of variation of the input parameters. Also, conclusions of the sensitivity analysis would differ if physical correlations among inputs were considered. (In the sensitivity analysis, the input parameters were varied independently of their physical relationships with other input parameters.) Over the general two-order-of-magnitude variation explored, the sensitivity analysis indicates that most COMIDA2 inputs have a small to moderate effect on the population dose and economic cost (e.g., less than 50 percent change). Only a few parameters (fewer than 20) have a relatively more important effect on dose and cost estimates. Those with more important effects mostly correspond to inputs that are linearly or inversely proportional to individual doses or population doses. Grains, leafy vegetables, and milk were identified as dominant products to the population ingestion dose in the baseline case. Grains are mostly dry foods, which could exhibit relatively high concentrations of radioactivity; leafy vegetables were assumed (due to scarce information) to assimilate (by a translocation process) radioactivity into plant tissues initially deposited on plant surfaces; and milk is an important component of people's diets supplied by local sources.

One aspect of the COMIDA2 model that differs from other food intake dose models is the consideration of farming seasons and the date of the fallout accident. Several farming dates are required inputs of the COMIDA2 model (e.g., start of the crop growing season, harvesting date, and start of livestock grazing season). In the MACCS-COMIDA2 implementation, up to nine fallout dates can be considered and spread over the year to examine different scenarios, and average statistics of the different accident dates are output. Dates defining the duration of the crop growing season (i.e., start of the growing season and harvesting date) have a relatively more influential effect than other agricultural dates on the population dose and economic cost MACCS outputs. However, the effect of varying the agricultural dates alone is secondary to the effect of assuming that a fallout event occurs near the beginning or near the end of a crop growing season.

The COMIDA2 model requires inputs to describe dynamic growth of plant products. Forage generally grows within a short period, on the order of 30 days. Using inputs reflecting a relatively fast maturity cycle for forage causes the root uptake of radioactivity to practically stop at approximately 30 days after the start of the pasture growing season. Such an approximation may underestimate the radioactivity intake by beef cattle and dairy cows from pasture. In reality, forage regrowth after grazing would continuously incorporate radioactivity from the soil well after the first 30 days from the start of the pasture growing season. To address this underestimation, a modification to the forage growth rate was proposed based on the duration of the grazing season instead of on the plant growing cycle. This approximation was not incorporated in the baseline case; instead, the baseline case considered the approximately 30-day pasture maturity cycle, as originally intended in the COMIDA2 model.

Some artificial and possibly unintended effects were noted by the use of holdup times (delay times from food production to food consumption) to allocate the consumption of crops between the current and the next accident year (years measured with respect to the fallout event). In

future updates to the COMIDA2 model, either disabling the use of the holdup time to allocate the food consumption among accident years or allowing this feature to be disabled through user input is recommended. This could be accomplished by adding a logical (true/false) input to enable/disable the inclusion of holdup in the proportion equation that computes the consumption allocation. Another unintended effect is associated with the assumption that crop foods are consumed during a period up to 365 days after the harvest (with radionuclide concentrations undergoing decay). In updates to the COMIDA2 model, limiting the decay time for crop radionuclide concentrations to the holdup time would avoid potentially underestimating intake (especially of short-lived radionuclides) and the associated dose and cost consequences.

The baseline inputs are regarded as reasonable inputs for generic consequence assessments. Site-specific inputs could be enhanced with respect to the general baseline inputs for individual food consumption rates and food production rates of locally consumed foodstuffs. Acquiring this information can be labor intensive, requiring local surveys. Inputs could be considered uncertain (i.e., defined through distribution functions to be sampled in the MACCS code), but care should be exercised in avoiding defining average total individual food consumption rates beyond reasonable levels. (For example, an average annual food consumption rate is on the order of 500 kg; the COMIDA2 model only tracks average individuals.) Nonetheless, the approach described in NUREG/CR–6613 to define consumption rates based on national agricultural statistics and census data is considered reasonable for consequence estimates.

Additional site-specificity could be incorporated in the definition of the *other animal* type. In the baseline case, it was assumed that the other animal type is an egg-laying hen, given that eggs are common in people's diets, can be locally produced, and could carry a higher radioactivity concentration than other protein products. The *other animal* could be used to simulate pork, when important to the local diet; however, general sources of information for pork products are more limited than for eggs. Finally, another input that could incorporate additional site-specificity is the diet of dairy cows. In the baseline case, it was assumed that dairy cows partially feed on pasture (which would cause contamination of milk from surface fallout). However, it is common practice to keep dairy cows fed with stored hay and other stored feeds obtained from non-local sources, which could reduce the exposure of cows to contamination.

CONTENTS

FIGURES

TABLES

ABBREVIATIONS/ACRONYMS

BIOMASS	BIOsphere Modeling and ASSessment
CNWRA®	Center for Nuclear Waste Regulatory Analyses
EPRI	Electric Power Research Institute
IAEA	International Atomic Energy Agency
INEL	Idaho National Engineering Laboratory
IUR	International Union of Radioecology
MACCS	MELCHOR Accident Consequence Code System
NRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
QA	Quality Assurance
PNNL	Pacific Northwest National Laboratory
SAIC	Science Applications International Corporation
SNL	Sandia National Laboratories
SOARCA	State-of-the-Art Reactor Consequence Analyses Project
TDM	total dry matter
USDA	United States Department of Agriculture

COMIDA2 PARAMETER NAMES

ALPHA	Foliar Interception Constant
BIC	initial areal biomass crops
BI	Initial areal biomass
BIH	Initial areal biomass hay
BIP	Initial areal biomass pasture
BMAX	maximum areal biomass
BMAXC	maximum areal biomass crops
BMAXH	maximum areal biomass hay
BMAXP	maximum areal biomass pasture
BSTAND	maximum standing biomass
CONSUM_RATES	consumption rates
CR	concentration ratio
GENERATION	variable to define decay chains
FD	dry-to-wet mass ratio
HOLDUPTM	human consumption delay or holdup times
NCUTOFF	number of cutoff half-lives
PROCLOSS	contamination reduction factor
PRODUC_RATES	production rates
PSR	root soil bulk density
PSS	surface soil bulk density
TCUT	hay cutting times
TC_BEEF	transfer coefficients for beef
TC_MILK	transfer coefficients for milk
TC_OTHER	transfer coefficients for other animal type
TC_POL	transfer coefficients for poultry
TEC	end of crop growing season, harvest date
TEL	end of livestock grazing season
TH	holdup time
THALF	radionuclide half-life
THBEEF	holdup time beef
THHAY	holdup time hay
THGL	holdup time grains and legumes
THMILK	holdup time milk

THOTHER	holdup time other animal type
THPOL	holdup time poultry
TINTM	last day that dairy cows are on pasture from the date of the fallout event
TSC	start of the crop growing season crops
TSH	start of hay growing season hay
TSL	start of livestock grazing season
TSP	start of pasture growing season pasture
TT	time of crop tillage
TVC	plant deposition factor
XR	thickness of root zone soil
XS	thickness of surface soil
ZKAB	foliar absorption rate constant
ZKAD	adsorption rate constant
ZKDE	desorption rate constant
ZKG	plant growth rate constant
ZKGC	plant growth rate constant crops
ZKGH	plant growth rate constant hay
ZKGP	plant growth rate constant pasture
ZKL	leach rate constant
ZKP	percolation rate constant
ZKR	resuspension rate constant
ZKRS	rainsplash rate constant
ZKW	weathering rate constant
ZSEN	senescence rate constant

ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA®) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No.31310018D0002. The activities reported here were performed on behalf of the NRC Office of Nuclear Regulatory Research, Division of Systems Analysis. The report is an independent product of CNWRA and does not necessarily reflect the views or regulatory position of the NRC. The technical and programmatic reviews by P. LaPlante and D. Pickett are recognized, as well as the formatting support by A. Ramos to prepare this document.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

Tasks were executed under the established CNWRA Quality Assurance (QA) Program, which is described in the CNWRA QA Manual, approved by the NRC, and audited for compliance annually. This QA program is implemented through Administrative Procedures (APs), Quality Assurance Procedures (QAPs), and Technical Operating Procedures (TOPs). Specific procedures that apply to this project include QAP–002, Review of Documents, Reports, and Papers; and QAP–014, Documentation and Verification of Scientific and Engineering Calculations.

DATA: All CNWRA-generated original data contained in this report meet the QA requirements described in the CNWRA QA Manual. Each data source is cited in this report, as appropriate, and should be consulted for determining the level of quality for those cited data.

ANALYSES AND CODES: The Windows version of the MACCS code (SNL, 2019), WinMACCS Version 3.11.2, was used to compute consequences of postulated accidents. The WinMACCS software is classified as “controlled software” in the CNWRA QA records. Consequence outputs and input values were extracted from WinMACCS output files. Mathematica® 12 was used to import values from WinMACCS output files, to plot results, and to compute sensitivity indices. Mathematica 12 is general use mathematical software classified as “exempt from control” by TOP–018. Relevant electronic files were archived with this report.

REFERENCE:

SNL. “MELCOR Accident Consequence Code System (MACCS).” Albuquerque, New Mexico: Sandia National Laboratories. 2019. <https://maccs.sandia.gov/maccs.aspx>
(Accessed date 1 May 2020).

1 INTRODUCTION

The purpose of this report is to update input parameters of the COMIDA2 food-chain model of the MELCOR Accident Consequence Code System (MACCS) (Chanin et al., 1998). The Windows interface to the MACCS code is named WinMACCS (McFadden, 2007). COMIDA2 is an extension of the stand-alone COMIDA model developed by the Idaho National Engineering Laboratory (Abbott and Rood, 1993, 1994), integrated to operate with MACCS. The original COMIDA model outputs radionuclide concentrations in agricultural foodstuffs per unit of fallout after a hypothetical radionuclide release accident. Crop concentrations (Bq/kg) are reported at the date of harvest, and animal food product concentrations are integrated time outputs during the year measured from the time of the accident (Bq-day/kg), both per unit of fallout (Bq/m^2). COMIDA outputs concentrations over multiple accident years, for multi-year simulations. COMIDA2 interfaces COMIDA with MACCS and converts the foodstuff concentrations to annual population doses (Chanin et al., 1998). COMIDA and COMIDA2 are distinct entities (e.g., there are inputs specific to the COMIDA2-MACCS interface that are not required to run the COMIDA model); however, for the purposes of this report it is considered that COMIDA2 includes the original COMIDA model. Consequently, "COMIDA2 input parameters," in this report refers to parameters of the original COMIDA model and the COMIDA2-MACCS interface.

Volume 2 of NUREG/CR-6613 describes recommended values for COMIDA2 input parameters (Chanin et al., 1998); however, the referred information in that NUREG is decades old. More recent information is available for some input parameters and updates to inputs to the COMIDA2 model are pertinent. A few tens of parameters are inputs to the COMIDA2 model; however, a number of parameters are radionuclide specific, plant specific, or animal specific. The total number of input values is more than 300; the number changes depending on the number of radionuclides relevant to the analysis.

Input parameters may be site-specific, but COMIDA2 is an aggregated model (capturing the physics of radionuclide mobilization at a high level) and therefore requires average, aggregated, or bounding inputs. Even if site-specific inputs and their variability across the region were known to a high level of precision, those inputs would have to be aggregated and averaged to be compatible with the COMIDA2 requirements. Average or aggregated input values are considered reasonable to support generic accident consequence assessments, especially recognizing the approximated nature of the COMIDA2 model. Relevant approximations of the COMIDA model that support the selection of input values are documented in this report.

Section 2 of this report identifies updated sources of information and provides tables with updated generic values. The information in Section 2 is organized according to parameter groups and the computational flow of the original COMIDA and COMIDA2 models. All of the COMIDA2 inputs are presented in Section 0. For each parameter group, population dose and economic cost estimates versus each parameter are presented in the form of "spider" plots. Sensitivity indices comprising linear fits to the data and the corresponding slopes of these fits were selected for the sensitivity summary in Section 3. Each subsection in Section 2 concludes with input parameter updates. The baseline case or reference case for the one-at-a-time sensitivity plots included all of the updated input values presented in Section 2 tables.

The sensitivity indices in Section 3 are compared to identify the most influential parameters to the population dose and economic cost, which are presented in the form of "tornado" diagrams. Most of the input parameters were varied over two orders of magnitude, which often exceeded the range of physical variability. The objective of this exercise was to examine the mathematical sensitivity of the model to one-at-a-time changes in input parameters, to explore model features

and interdependencies, and to explain the meaning of the COMIDA2 input parameters. The reported sensitivity indices would change if domains of physical variability in the COMIDA2 inputs were considered, if the baseline case inputs changed, or if physical correlations between input parameters were accounted for. (In the sensitivity runs, the input parameters were independently varied.)

To develop the spider plots, MACCS was executed in Monte Carlo mode, with 20 or 50 realizations independently varying one-parameter-at-a-time. The MACCS input source term was updated to incorporate information from Appendix B in the State-of-the-Art Reactor Consequence Analyses Project (SOARCA) Volume 2, NUREG/CR–7110 (SNL, 2012). NUREG/CR–7110 Volume 2 includes estimates of offsite radiological consequences caused by potential severe reactor accidents at the Surry Power Station in Virginia. For each run that was executed in Monte Carlo mode, a single parameter was defined to follow a log-uniform distribution ranging by a factor of 10 above and below the baseline value (i.e., two orders of magnitude variation centered around the baseline value). The baseline inputs were the recommended updated input values in Section 2. For a few parameters, uniform distributions were more appropriate (e.g., parameters corresponding to fractions between 0 and 1, and farming dates) to perform the input parameter sweeps in a single Monte Carlo run. For parameters that are radionuclide-dependent (e.g., concentration ratios, transfer coefficients, and foliar absorption rates), distributions were input for all radionuclides. However, the MACCS rank-correlation function was selected so that the values selected were perfectly correlated in each realization (e.g., if a sampled input value was high for one radionuclide, all other radionuclides were also sampled at correspondingly high values). This radionuclide perfect rank-correlation strategy was implemented for examining trends resulting from the variation of a parameter (e.g., concentration ratio and transfer coefficient), instead of examining effects of individual radionuclides to the population dose and economic cost estimates.

As previously stated, the baseline input case considered in the sensitivity runs included the parameter updates recommended in this report. The process to construct the sensitivity runs was tedious, requiring several steps including opening the WinMACCS graphic unit interface, locating the input parameter, performing adjustments, and launching the multi-realization run. Each curve in the sensitivity plots corresponds to a single WinMACCS multi-realization run that required approximately 15 minutes of computer time to be completed (50 realizations per multi-realization run). Thus, data for a plot that includes 4 curves took approximately one hour of computer time to be generated. To prepare the sensitivity plots, computer scripts were developed to extract the information from text files output by WinMACCS (files tbl_outStat.txt and SampleRank.out). For each plot, it was verified that the correct input was present in the baseline file and the correct range of variation was executed in the multi-realization runs. In case an error in any of the COMIDA2 baseline inputs was detected (i.e., an unintended input differing from updated values in Section 2 tables), the error in the baseline input file (a WinMACCS database file with extension .mxd) was corrected and all the multi-realization runs to prepare the Section 2 plots were executed again.

2 COMIDA2 INPUT PARAMETER ANALYSIS

As stated in the introduction, COMIDA and the COMIDA2-MACCS interface are distinct entities; however, for the purposes of this report, the *COMIDA2 model* refers to the original COMIDA food-chain model (which outputs radioactivity concentrations in food products) plus the food-intake dose model addressed by the COMIDA2-MACCS interface (which outputs individual and population doses). When referring to *COMIDA2 input parameters*, this report means input parameters of the original COMIDA model and the additional parameters of the COMIDA2-MACCS interface. For a clear distinction of which parameters are inputs to the COMIDA food-chain model or to the COMIDA2-MACCS interface, the reader is referred to NUREG/CR-6613 Volume 2 (Chanin et al., 1998). All of the COMIDA2 input parameters discussed in this chapter are input through the WinMACCS graphic interface for the food-chain model. All of the parameters are grouped in the WinMACCS interface under a *COMIDA2* label.

The main components of the original COMIDA model are summarized in Figure 2-1. Soil is modeled as three compartments—representing surface soil, labile soil, and fixed soil—and plants are modeled as two compartments—representing plant internals and plant surface. The model assumes compartments are instantaneously well-mixed, that is, radionuclides in a compartment are instantaneously uniformly distributed, without any concentration gradients. Compartments exchange radionuclides back and forth according to various physical and biological processes. In the case of a radionuclide release accident, the model assumes radioactive fallout initially contaminates the surface soil compartments and the plant surfaces. Radionuclides are transferred to other compartments as time elapses, controlled by the physical and biological transfer rates. From the plants, radionuclides are transferred to animals by the consumption of feed products. COMIDA outputs radionuclide concentrations in foodstuffs per unit of fallout. More specifically, the original COMIDA model outputs the radionuclide concentration (Bq/kg) at the harvest date for five crops, and the time-integrated concentration in foods of animal origin (Bq-day/kg) over the year measured from the time of the radionuclide release accident, both per unit of fallout (Bq/m^2). The COMIDA model outputs concentrations in yearly intervals for multi-year simulations.

COMIDA2 accounts for radionuclide decay and ingrowth during the delay time prior to food consumption by humans and animals (e.g., food storage time) and removal of radioactivity during food processing (e.g., removal of corn husks). COMIDA2 uses food production rates, the event fallout intensity (in units of Bq/m^2), and concentration to dose conversion factors (in Sv/Bq units) to compute individual doses and annual population doses associated with food intake. MACCS includes an interdiction model that, for example, stops production and destroys foods when food is contaminated above certain levels, which also affects the population dose from food and the economic cost. The interdiction of food is based on a user-specified individual dose level assuming that an individual consumes a user-specified level of a mix of foodstuffs from the contaminated land.

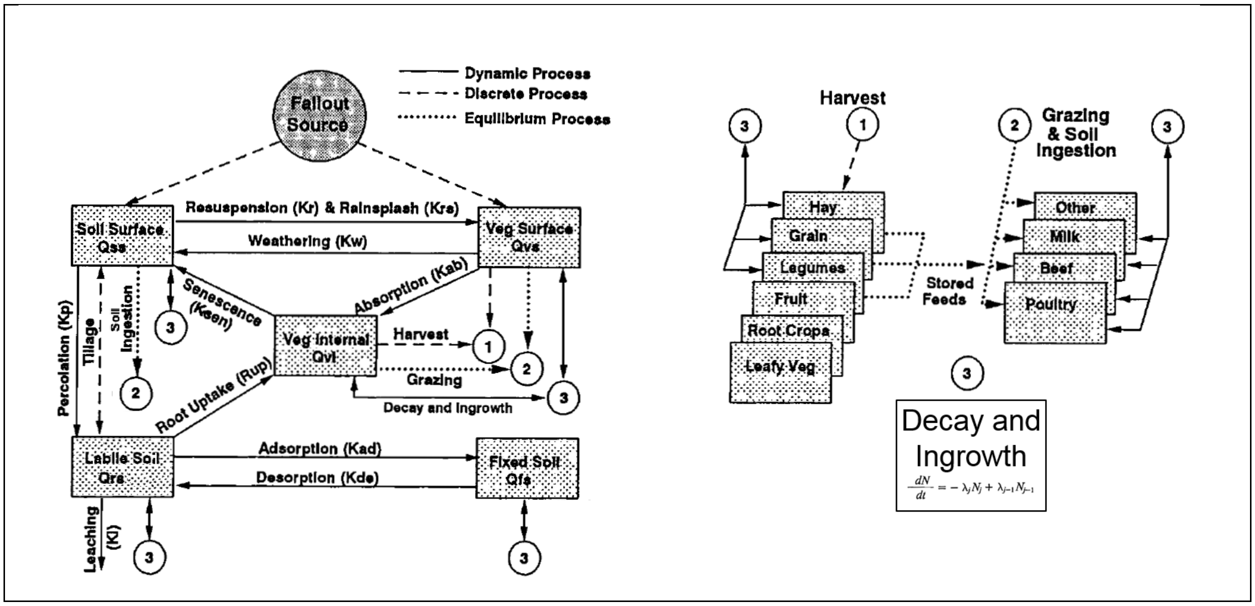


Figure 2-1. Compartment model implemented in the COMIDA food-chain model (from Abbott and Rood, 1993, 1994)

More detailed descriptions of individual input parameters are provided in the following sections, organized according to the direction of radionuclide transfer. The parameter sections starting at Section 2.3 begin with the topic fallout deposition and plant interception, then continue with contaminant transfer from soil and plant surfaces to deep soil and plant internals, and end with radionuclide transfer to animals and to humans. Section 2.1 describes the approach to parameter variation and the computation of indices for the sensitivity analysis, and Section 2.2 presents the radionuclide definition and decay chains tracked in COMIDA2.

2.1 Approach for One-Parameter-at-a-Time Runs for Sensitivity Analyses

The updated inputs to the COMIDA2 model are referred to as baseline inputs. To evaluate sensitivities of outputs (population dose and total economic costs) to the input parameters, multi-realization runs of the MACCS code varying only one parameter were executed and plots of the population dose and economic cost versus the input parameter were prepared. The total population dose included contributions from all dose pathways addressed by MACCS: external exposure to radionuclides in the released air plume, external exposure from radionuclides deposited on surface or groundshine, internal exposure through inhalation, and internal exposure through ingestion of contaminated water and food. Information to prepare scatter plots was extracted from MACCS output files SampleRank.out (sampled input values of the parameter) and tbl_outStat.txt (population dose and total economic cost). More specifically, the outputs were extracted from the lines with the labels

"Population Dose (Sv)"	"Evacuation Overall L-ICRP60ED [0.,1609.34](km)"
"Total Economic Costs ($)"	"Evacuation CHRONC [0.,1609.34](km)"

The total population dose includes contributions from the evacuation cohort and chronic (long-term) population doses, from all primary pathways tracked in the MACCS code (cloudshine, groundshine, inhalation, and ingestion of food and water). The total economic cost includes population- and farm-dependent costs, including costs associated with decontamination, interdiction, and land condemnation. Sensitivity analyses, including

information not exclusively associated with the food ingestion pathway, were performed to gain insight of the effects of COMIDA2 inputs on overall the consequences calculated by MACCS.

For most input parameters, the explored domain of variation ranged from baseline/10 to baseline×10 (i.e., two order of magnitude variation around the baseline value). Some exceptions were implemented; for example, parameters that represent fractions were sampled between 0 and 1, and agricultural dates were sampled with ± one month. The varied parameter was sampled using a log-uniform distribution, or uniform distribution for the exceptions.

A number of inputs, such as the Leach Rate Constant (symbolized as ZKL), are defined in MACCS as radionuclide specific (more accurately parameter values are element specific). To focus attention on the sensitivity to the parameter as a whole (and not on the sensitivity to specific radionuclides), the MACCS code was executed in Monte Carlo mode, sampling the values of the parameter of the different radionuclides in a perfectly correlated manner, using the rank-correlation function of the MACCS code. Figure 2-2 is an example of correlated sampling for the ZKL parameter. The number in parenthesis in the vertical and horizontal axis labels of the scatter plots in Figure 2-2 represent different radionuclides [e.g., ZKL(2), ZKL(10), ZKL(11), ZKL(15), ZKL(16)]. Applying the MACCS rank-correlation function in this way causes any scatter plot with ZKL pairs of different radionuclides to approximate a straight line (the straight line is not perfect because MACCS applies random sampling for each radionuclide and then sorts the values by rank).

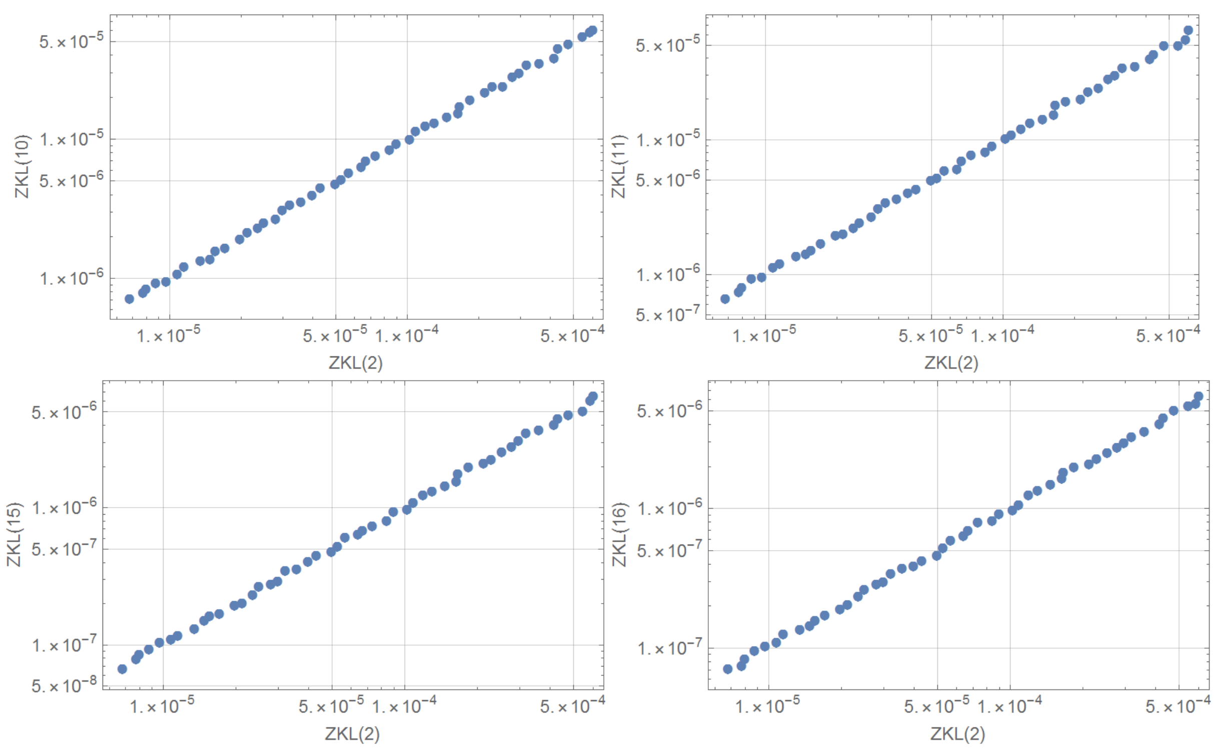


Figure 2-2. Example of correlated sampling implemented in the MACCS code. The horizontal and vertical axis in each plot correspond to values of the parameter ZKL for two different radionuclides.

To prepare scatter plots of total dose or economic cost versus input parameters that are radionuclide specific (such as ZKL), any radionuclide could be selected to represent the input parameter. However, in this report the input values were first normalized by the reference

values for each radionuclide, and then the normalized values were averaged over all radionuclides. For example, the approach for ZKL was first computing the normalized value ZKL(1)/reference(1), ZKL(2)/reference(2), ZKL(3)/reference(3), and so on, and then computing the average of the normalized values (the number in parenthesis represents a different radionuclide). In the sensitivity plots in this report, for input parameters that are radionuclide specific, the horizontal axis represents the average over all radionuclides of the normalized values. Figure 2-3 shows example scatter plots with the Leach Rate Constant (ZKL) on the horizontal axis (normalized ZKL averaged over all radionuclides). Finally, a logarithmic function was applied to the horizontal scale to transform the domain to span from −1 to 1.

The vertical scale of the plots in Figure 2-3 represents the relative change with respect to the baseline value of the population dose or baseline value of the total economic cost. In this example, despite the two order of magnitude variation in ZKL, the population dose varied by less than 1 percent, and the economic cost negligibly changed. The population dose monotonically decreases with increasing ZKL: high leach rate values correspond to scenarios where radionuclides are quickly transferred to deep soil, where they become inconsequential to the dose estimates.

A sensitivity index was computed as follows. Linear fits to the relative dose change versus log10(normalized ZKL) and to the relative cost change versus log10(normalized ZKL) passing through the origin were computed. The resulting fits are displayed in Figure 2-3. The slopes (-0.005 and -1.007×10^{-6}) were selected as the sensitivity indices. The linear fits are not intended to be accurate; instead, they were used only to compute first-order indices (slopes) measuring the relative change in the population dose and the economic cost when the ZKL parameter was varied over two orders of magnitude around a reference value. A similar approach to compute sensitivity indices was used for all parameters analyzed in this report.

For some parameters it was not possible or reasonable to select a domain spanning from reference/10 to reference×10. For example, mass ratios of dry to wet plant food products are less than 1. The reference values for the different plant products were of the order of 0.1; the dry to wet ratios were varied from 0 to 1 for the one-parameter-at-a-time runs. The range of variability of the input parameter, in this example, was not symmetrical with respect to the reference values. For the sensitivity analyses, the domain was linearly transformed so that the reference value was mapped to 0 and the upper value of the domain was mapped to 1. The linear transformation was [*variable–reference*]/scale, with *scale* a factor selected to match the mapping requirements (i.e., the transformed variable must be 1 for the maximum sampled value). For example, for a dry to wet ratio with a reference value 0.3, the scale factor was set to 0.7. Figure 2-4 shows a scatter plot of the relative change in the dose versus the wet to dry mass ratio. A value 0 on the transformed horizontal axis corresponds to the reference value (similarly, in Figure 2-3 a value of 0 on the transformed horizontal axis corresponds to the reference value). The sensitivity index was defined as the slope of the linear fit. Figure 2-3 includes information on several plant products; one sensitivity index was computed for each plant product.

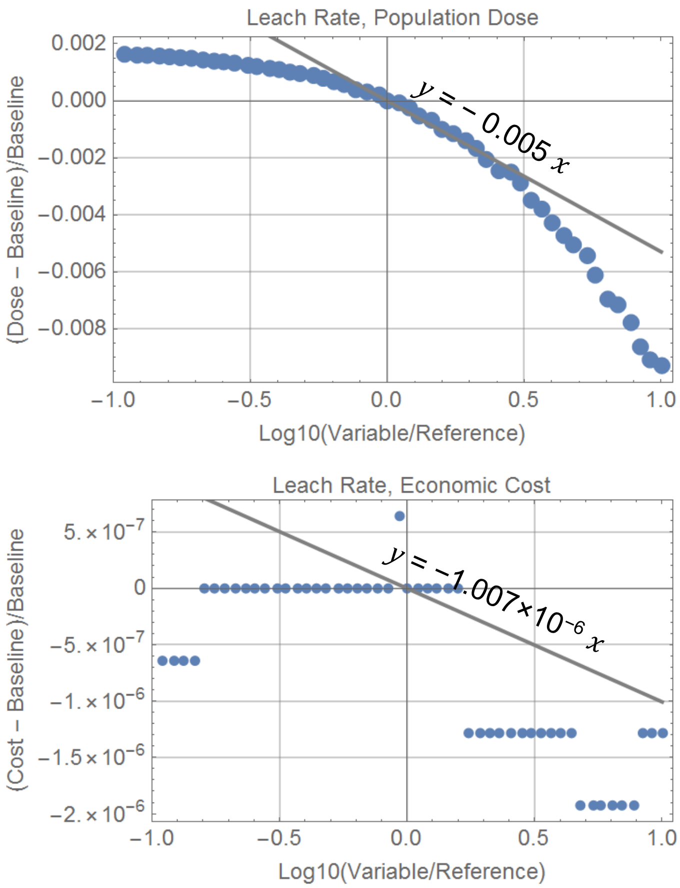


Figure 2-3. Example of computation of linear fits to define sensitivity indices

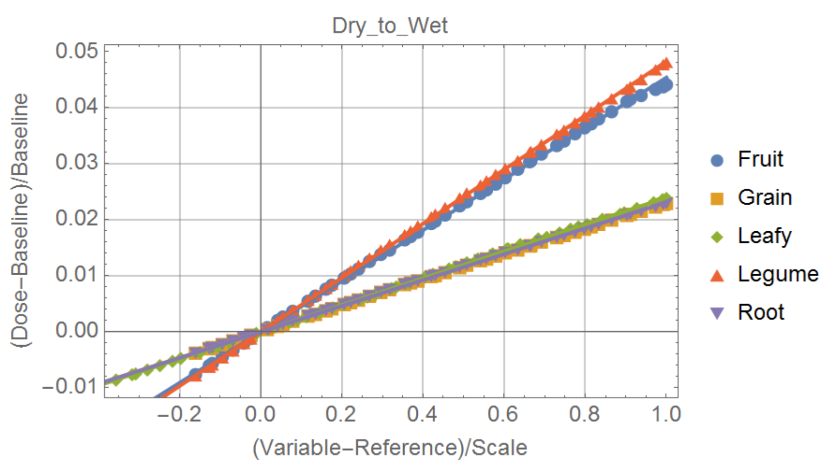


Figure 2-4. Example of computation of linear fits to define sensitivity indices for exceptions (cases of less than two-order of magnitude variation around the reference value)

2.2 Nuclides (NUCLIDES), Half-Lives (THALF), Half-Live Cutoff (NCUTOFF), and Decay-Chain Definition (GENERATION)

The title parameters characterize the radioactive isotopes considered in the COMIDA2 food chain model. The set of radionuclides included in example files distributed with WinMACCS is a reasonable set of radionuclides for generic use for consequence assessments of release accidents involving nuclear power reactors. The radionuclide set for the food intake dose model in the updated input file was extracted from the point estimates Sample Problem LNT input file, which is a radionuclide set consistent with studies such as the State-of-the-Art Reactor Consequence Analyses Project (SOARCA) (SNL, 2012). The radionuclides in the Sample Problem LNT input file and half-lives are listed in Table 2-1.

The parameter NCUTOFF is the number of nuclide half-lives to stop tracking a particular radionuclide in the calculations after reaching the cutoff simulation time. Large NCUTOFF values may yield high run times; and care should be exercised in selecting reasonable values for NCUTOFF to enhance the efficiency of runs. In the Sample Problem LNT input file NCUTOFF=10 for most radionuclides, and NCUTOFF=20 for Sr-89.

Table 2-1. Radionuclides considered in in the Sample Problem LNT input file

Radionuclide	THALF, half-life (days)
Sr-89	50.5
Sr-90	1.06×10^4
Ru-103	39.28
Ru-106	368.2
Te-127m	109
Te-129m	33.6
Te-132	3.26
I-131	8.04
I-133	0.8666
Cs-134	753.1
Cs-137	1.1×10^4
Ba-140	12.74
La-140	1.68
Ce-144	284.3
Am-241	1.85×10^5
Pu-238	3.2×10^4
Pu-239	8.79×10^6
Pu-240	2.39×10^6
Pu-241	5260
Cm-242	162.8
Cm-244	6615

The Sample Problem LNT input file considers only two 1-progeny decay chains: $^{140}Ba \rightarrow {}^{140}La$, and $^{241}Pu \rightarrow {}^{241}Am$. COMIDA2 Decay chains are defined in the WinMACCS interface through the variable GENERATION.

2.3 Initial Fallout Proportions and Plant Growth Model: Initial Areal Biomass (BI), Maximum Areal Biomass (BMAX), Maximum Standing Biomass (BSTAND), Plant Growth Rate Constant (ZKG), and Foliar Interception Constant (ALPHA)

This section describes plant growth and relationship to the initial proportion of fallout on plant surfaces and soil.

2.3.1 Mathematical Model for Plant Growth and Initial Fallout Fractions

The parameters associated with the initial fallout proportions and the plant growth model are the initial areal biomass (BIC for five crops, BIP for pasture, and BIH for hay), maximum areal biomass (BMAXC, BMAXP, and BMAXH), maximum standing biomass (BSTAND), plant growth rate constant (ZKGC, ZKGP, and ZKGH), and foliar interception constant (ALPHA, specified for five crops, hay, and pasture). These parameters are used to define the amount of crops (fruit, grain, leafy vegetables, and legumes), pasture, and hay that can be grown per unit of land area, as a function of time. These parameters are also used to define yields of crops, pasture, and hay, and the relative surface coverage of a plant type to define the fraction of fallout directly depositing on plant surfaces or on soil. The maximum standing biomass is the aboveground total biomass, whereas the maximum areal biomass is the edible portion of a plant that is harvested, whether above or below ground (e.g., lettuce is all above ground; carrots and potatoes are below ground). The plant biomass as a function of time (with respect to the start of the growing season) is computed with the following logistic function (Abbott and Rood, 1993, 1994)

$$B(t) = \frac{B_m}{1 + \frac{B_m - \mathrm{BI}}{\mathrm{BI}} e^{-\mathrm{ZKG}\, t}} \tag{2-1}$$

where

$B(t)$	—	Biomass as a function of time (time measured with respect of the start of the growing season) (dry kg/m^2)
B_m	—	BMAX (maximum areal biomass) or BSTAND (maximum standing biomass) (dry kg/m^2)
BI	—	Initial areal biomass (dry kg/m^2) (BIC, BIP, or BIH)
ZKG	—	Plant growth rate constant (1/yr)

A typical biomass function $B(t)$ is displayed in Figure 2-5(a). The parameter BI defines the initial mass at the start of the growing season. B_m (BMAX or BSTAND) defines the function plateau, and ZKG controls the growth rate. Figure 2-5(b) shows the time derivative $B'(t)$; $B'(t)$ controls the transfer rate of radionuclides from the labile soil (root soil) to the edible plant parts. When the derivative is low or close to zero [e.g., near the right plateau in the $B(t)$ curve] there is limited or no transfer of radionuclides from the soil to the plant tissues through the roots.

BSTAND is the maximum standing biomass aboveground per unit of area, and BMAX is maximum edible biomass (above and below ground) per unit of area. Individual values of BMAX are input in WinMACCS for the seven plant products (five crops, pasture, and hay). On the other hand, individual input values of BSTAND are only required for five crop categories tracked in COMIDA (fruit, grain, leafy vegetables, and legumes). The COMIDA model internally sets BSTAND = BMAX for pasture and hay; in other words, input BSTAND values for pasture and

hay are defined through the input BMAX values, the user is not required to provide separate inputs of BSTAND for pasture and hay.

(a)

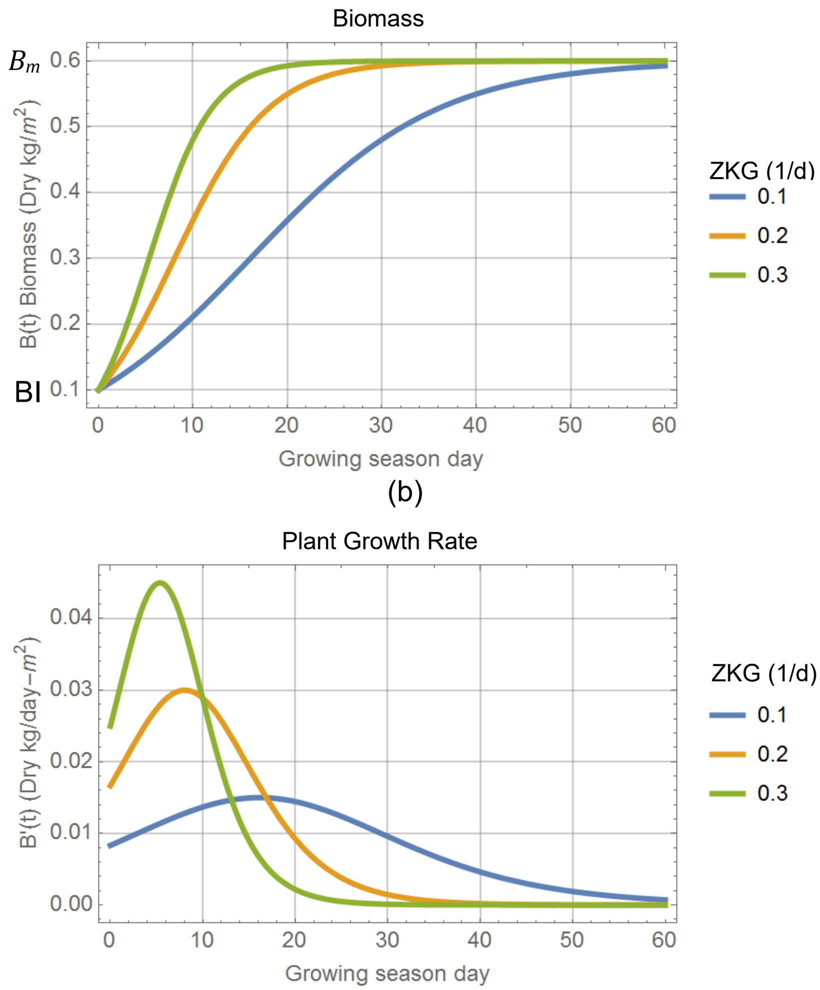


Figure 2-5. (a) Plant biomass $B(t)$ as a function of time, and (b) plant growth rate $B'(t)$ as a function of time. Example curves are presented for three growth rate constant (ZKG) values.

The COMIDA model executes the Eq. (2-1) with B_m = BSTAND to define the fraction of fallout on plant surfaces and on the surface soil. The fraction of fallout initially deposited on vegetation at the time of the event t=t_e (typically referred to as the interception fraction or crop interception fraction in other radiological assessment models) is computed as

$$FV(t_e) = 1 - e^{-\alpha\, B(t_e)} \qquad (2\text{-}2)$$

where α (named ALPHA in WinMACCS) is an empirical parameter referred to as the foliar interception constant (m^2/kg) (Abbott and Rood, 1993). $B(t)$ is defined in Eq. (2-1) with B_m = BSTAND. Different values of α are required for the five crop categories, hay, and pasture. The complementary fraction, $1 - FV(t_e) = e^{-\alpha\, B(t_e)}$ is the fraction of fallout directly on the surface soil. ALPHA is influenced by the plant surface area, fallout particle size, type of deposition (wet vs. dry), and the physicochemical form of the contamination. The recommended value for

ALPHA in NUREG/CR–6613 (Chanin et al., 1998) is 3 $m^2\ kg^{-1}$ for most vegetation, based on grass canopy (Miller, 1980), except for fruit. The recommended value for fruit is a factor of 10 smaller, 0.3 $m^2\ kg^{-1}$ (Pinder et al., 1987). The 3 and 0.3 $m^2\ kg^{-1}$ values were calculated using limited observations of selected vegetation, and not covering the range of particle sizes that might be applicable to a nuclear reactor accident. Figure 2-6 shows two examples of deposition fractions with different values of ALPHA or α. In case of small values of ALPHA, most fallout is initially deposited on the soil. For cases of large ALPHA, the deposition fraction depends on the event time. If the event time is early in the growing season, most fallout is deposited on soil; if late in the growing season, most of the fallout directly affects the plant surfaces.

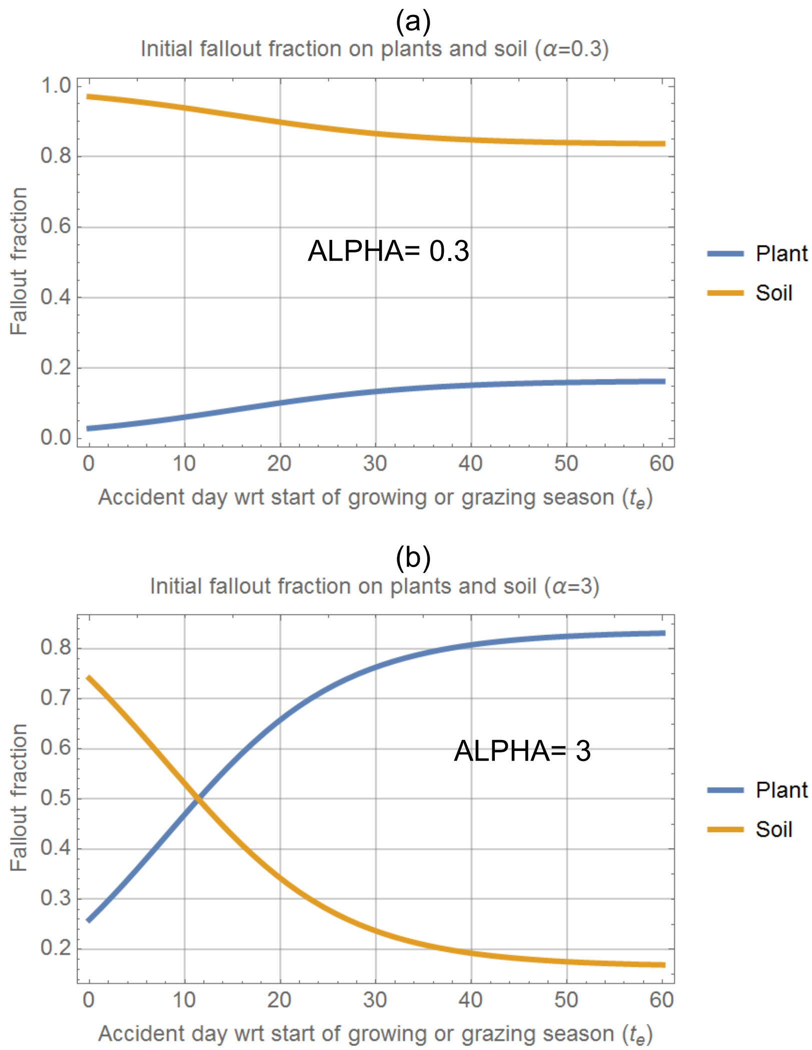


Figure 2-6. Fallout deposition fraction as a function of the event day with respect to the start of the growing season for (a) ALPHA (α, foliar interception constant) = 0.3 and (b) ALPHA = 3.

COMIDA tracks the beginning and end of the growing season and the livestock grazing season. If the event occurs before the growing season, FV=0 for the five crops (i.e., radioactive fallout is deposited on soil). FV is computed with the value of BI (initial biomass) for hay and pasture if the event occurs before the hay growing season or livestock grazing season. If the event is after the crop growing season or the livestock grazing season, FV=0 for the five crops, hay, and pasture (i.e., radioactive fallout is assumed entirely deposited on the surface soil compartment).

For the initial fallout fractions, COMIDA accounts for the time of the event, t_e, with respect to the crop growing season and the grazing season. As previously described, Eq. (2-1) is only evaluated at t_e, to establish the initial fractions of radioactive fallout on plant surfaces and the surface soil. On the other hand, COMIDA also implements dynamic computations to track relative radionuclide concentrations in five compartments (three soil compartments and two plant compartments) of the COMIDA model (Figure 2-1). A root uptake model is used to define the rate of radionuclide transfer from the labile soil to the plant, which rate is proportional to the derivative $B'(t)$ and inversely proportional to the labile soil mass per unit of area (Abbott and Rood, 1993, Section 4.2). To compute the rate of root transfer, $B(t)$ and $B'(t)$ are evaluated using B_m=BMAX in Eq. (2-1). In COMIDA, BMAX and BSTAND are independent inputs (except for hay and pasture), and it is up to the user to ensure that those inputs are consistently defined. It is noted that COMIDA requires dry weight input parameters.

COMIDA implements the five-compartment model (Figure 2-1) for each of the seven plant products (five crops, hay, and pasture). The five compartments for a plant product are independent of the five compartments of another plant product. In other words, radionuclides that are initially deposited on legumes only contaminate legumes during the COMIDA simulation time. A process such as crop rotation is not considered in the COMIDA model, which would cross-contaminate crops. This assumption of independence is required to maintain linearity of radionuclide concentrations in food products and the strength of the source. The COMIDA2-MACCS interface simply scales the COMIDA outputs by the fallout concentration (Bq/m^2 units) and by the total fallout amount (Bq units), as a post-processing step, to compute radionuclide concentrations in food products and the associated individual and population doses (Section 0). The percentage of farmland is specified in the MACCS Site Input file, and COMIDA2 assumes that the farmland is proportioned among seven plant products (five crops, pasture, and hay). The COMIDA2 model assumes that the local production of farm products equals the local consumption of food products (Chanin et al., 1998, Volume 2, p. 2-4) to compute population doses (Section 0).

2.3.2 Initial Areal Biomass (BI), Maximum Areal Biomass (BMAX), and Standing Biomass (BSTAND)

The initial areal biomass (BI) is an initial condition for the plant growth model. Agricultural fields are plowed before spring planting; and low values are reasonable generic values for initial condition. In the baseline case, it was assumed BI=0.01×BMAX. Figure 2-7 shows the relative change in population dose and economic cost versus the normalized initial areal biomass. (The parameter BI must be less than BMAX; MACCS does not issue any message warning the user of incorrect inputs. In case of incorrect inputs, MACCS outputs large doses and costs.) The BI value is associated with radioactivity remaining in plants after each growing and harvest cycle. The individual dose tends to increase with increasing values of BI for most plant products, except for pasture. The economic cost is highly dependent on the crop disposal area (lower left plot in Figure 2-7), and both increase with increasing values of BI [except for BI(pasture)]. The inflection point and decreasing population dose versus BI(grain) correlates with the inflection

point in the crop disposal area and steeper increases in crop disposal area at large values of BI(pasture)

The decreasing trend in population dose versus BI(pasture) (top left plot in Figure 2-7) also correlates with decreasing milk disposal areas (lower right plot in Figure 2-7). This decrease indicates a decreasing individual dose with increasing values of BI(pasture). The COMIDA model of pasture growth and assimilation of radioactivity deposited in soil is slightly different than the corresponding COMIDA model for the other plant products. The COMIDA model incorporates a senescence process for pasture: radioactivity in pasture goes back to the surface soil at the end of the growing season (other plant products do not account for senescence; radioactivity is assumed to remain in plant tissues). Cases of high BI(pasture) incorporate less radioactivity in the pasture from the soil after the pasture growing period than cases of low BI(pasture). This causes the individual dose and population dose to decrease with increasing values of BI(pasture) (top left plot in Figure 2-7). The decreasing trend in the population dose reflects decreasing individual doses with increasing BI(pasture).

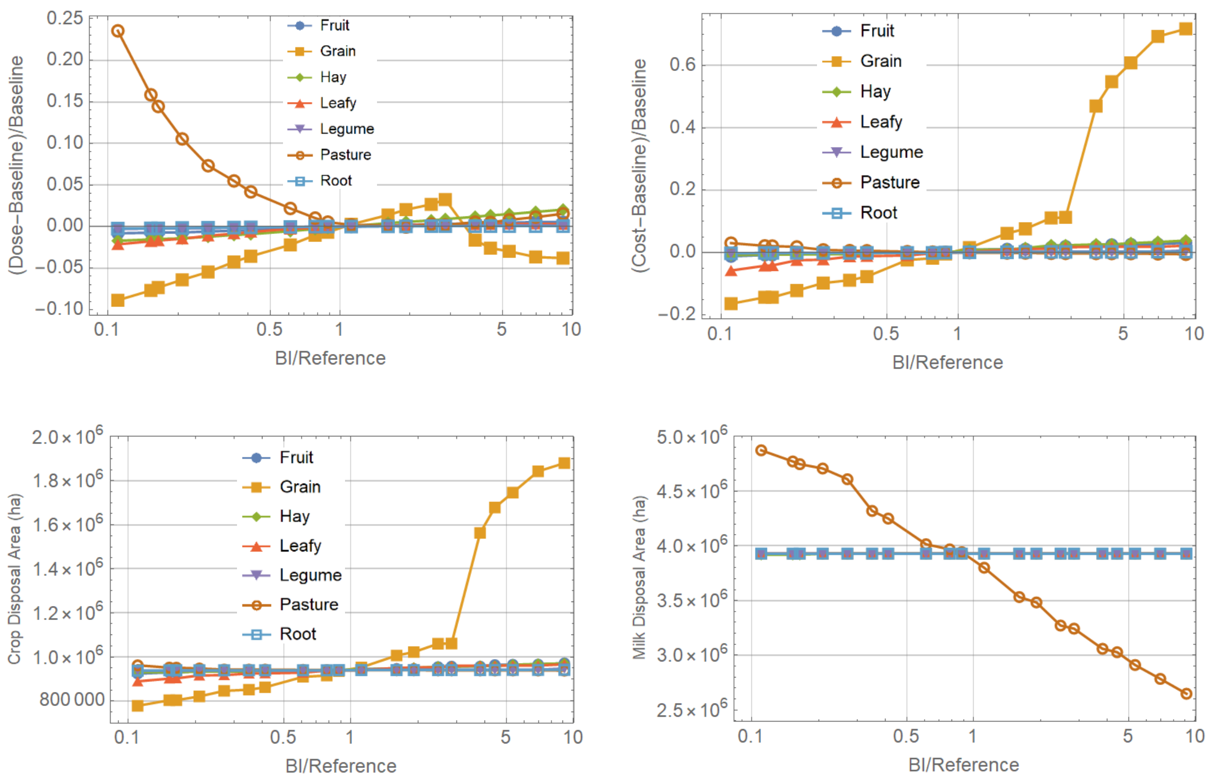


Figure 2-7. Relative change in population dose and economic cost versus the normalized initial areal biomass (BI), and crop disposal and milk disposal areas versus BI.

Figure 2-8 displays the relative change in population dose and economic cost versus the normalized maximum areal biomass. (BMAX must be greater than BI; however, MACCS does not issue any warning to the user to prevent incorrect inputs. In case of incorrect inputs, MACCS outputs large population doses and economic costs.) For the five crops (fruit, grains, leafy vegetables, legumes, and roots) BMAX is related to the rate of contaminant uptake from labile soil to the plant roots [root uptake is proportional to the derivative $B'(t)$]. Also, BMAX is used to define the contaminant concentration per unit of dry-weight [Bq/kg, Eq. (2-23)], causing individual dose estimates to decrease with increasing BMAX. In the specific cases of hay and

pasture, BMAX is also related to the proportion of fallout directly deposited on plants or on soil: increasing BMAX increases the initial amount of fallout directly deposited on plants. Plant concentrations and dose results can increase to levels sufficient to trigger the interdiction model causing local maxima in the population dose plot (top left plot) in Figure 2-8.

The crop disposal area and milk disposal area versus BMAX are provided in Figure 2-8 to rationalize the population dose trends. The decreasing trends in the crop disposal and milk disposal curves indicate that the individual dose decreases with increasing BMAX. At low values of BMAX, radionuclide concentrations in leafy vegetables and grain food products are high, causing high extent of crop disposal and milk disposal areas, and the increasing trend in the population dose versus BMAX(leafy) and BMAX(grains) in the segment labeled as 1 in the dose plot in Figure 2-8. The decreasing trend segment labeled as segment 2 in the population dose curve in Figure 2-8 simply arises from the decreasing individual dose with increasing values of BMAX. Competing elements arise from land condemnation, land decontamination, farm interdiction, and milk disposal that cause irregular trends in the total population dose.

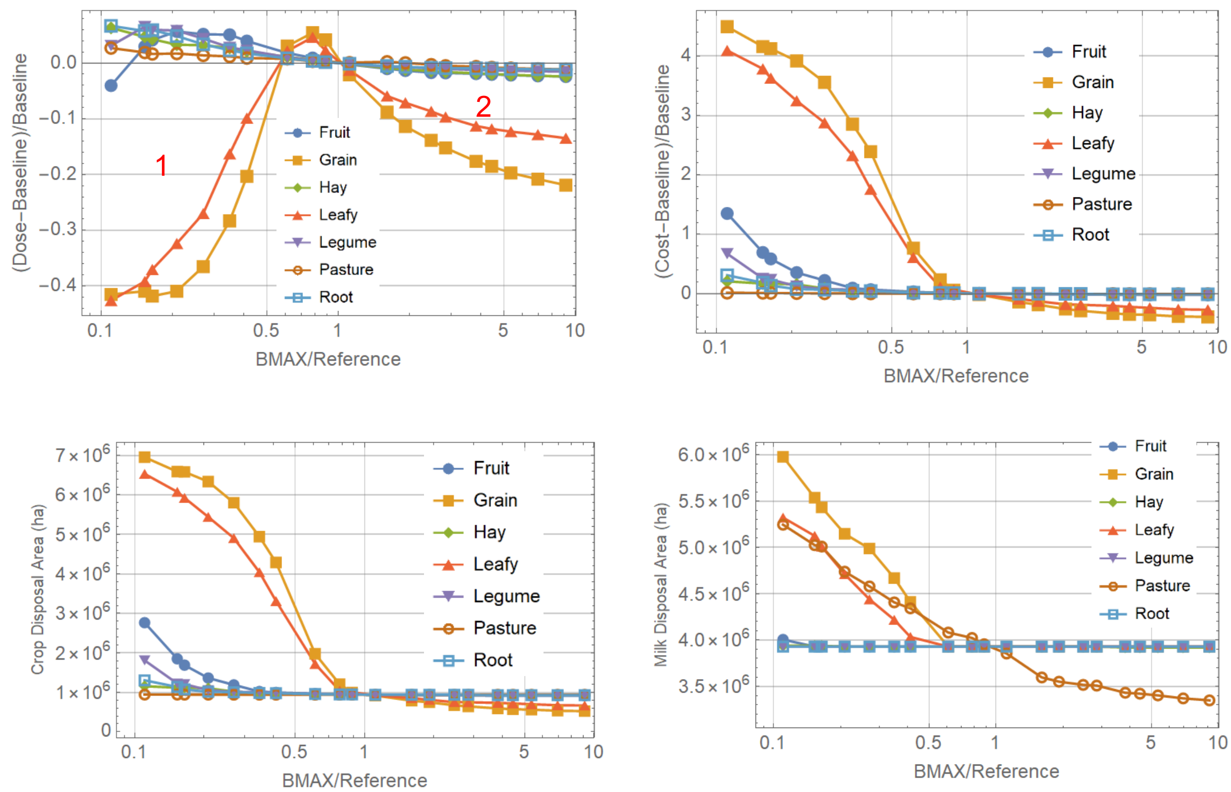


Figure 2-8. Relative change in population dose and economic cost versus the normalized maximum areal biomass (BMAX), and crop disposal and milk disposal area versus BMAX.

The sensitivity of the population dose and the economic cost to the maximum standing biomass parameter (BSTAND) is displayed in Figure 2-9. With increasing values of BSTAND, a higher proportion of fallout directly deposits on plant surfaces, which is eventually incorporated in plant tissues by translocation, causing increasing values of the individual dose. The increasing trends in the plots in Figure 2-9 are consistent with increasing individual dose with increasing values of BSTAND.

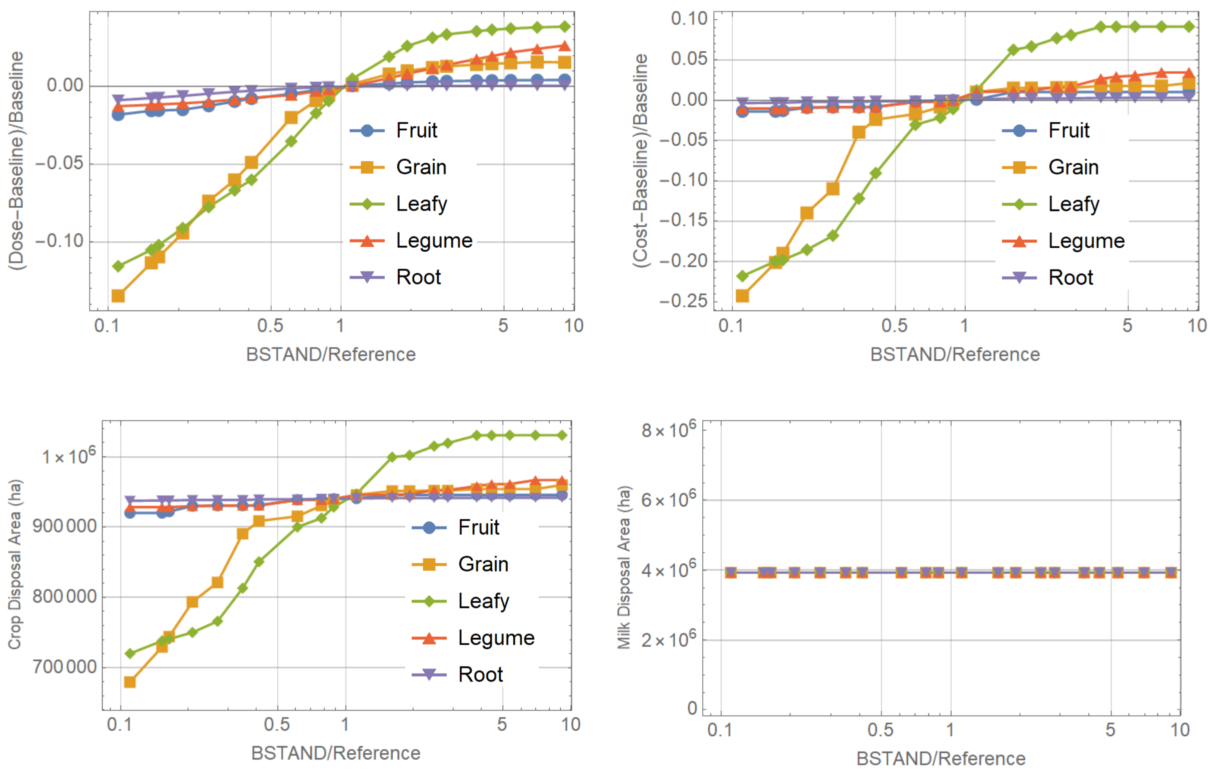


Figure 2-9. Relative change in population dose and economic cost versus the normalized maximum standing biomass (BSTAND), and crop disposal and milk disposal area versus BSTAND.

BI, BMAX, and BSTAND Parameter Updates

The values of BI, BMAX, and BSTAND are interrelated, and should be selected in consistent manner. NUREG/CR–6613 (Chanin et al., 1998) suggest values of the initial areal biomass, BI, equal to 0.015, 0.07, and 0.08 kg/m^2 for crops (grains, leafy vegetables, root crops, fruits, and legumes), pasture, and hay, respectively, based on PATHWAY work by Whicker and Kirchner (1987). In this update, to fully examine the effect of a plant growing season, it is recommended to set BI = 0.01 BMAX (i.e., it is assumed that the biomass increases by two orders of magnitude from the initial value over the growing time). As a caveat, Eq. (2-1) outputs zero in the limit when BI equals zero; thus, BI equal zero must be avoided as input. Lower values of BI than 0.01 BMAX have the effect of flattening the left tail of the logistic curve [e.g., Figure 2-5(a)], and in effect inadvertently decrease the effective duration of the growing season.

The maximum areal biomass, BMAX, values in NUREG/CR–6613 (Chanin et al., 1998) are based on work by Shor et al. (1982), who analyzed the 1974 Census of Agriculture information. More recent work documented in NUREG/CR–5512, Volume 3 (Beyeler et al., 1999) considered crop yields of edible crops. Table 6.1-1 in Bechtel SAIC (2004a) compiles information equivalent to the maximum areal biomass, per plant, including cumulative distributions and accompanying dry-wet-weight ratios. The Land Cover/Plant Growth Database (Neitsch et al., 2002) is another compendium from which plant growth rates can be inferred. Site-specific values may be obtained from the National Agricultural Statistics Service database that is maintained by the United States Department of Agriculture (USDA, 2012). However, it is highlighted that COMIDA tracks generic, blended, food categories and that yield rates and growth rates of specific plant

products exhibit limited variability. General, average values, of yield rates and growth rates are considered sufficient for consequence assessments. Site-specific information may be implicitly incorporated by the consideration of local human consumption rates and total production rates of plant products required for the individual dose and population dose computations (Section 0 of this report).

Generic updated values of BMAX, BSTAND, and BI are listed in Table 2-2, based on NUREG/CR–5512, Volume 3 (Beyeler et al., 1999) and in the report Agricultural and Environmental Input Parameters for the Biosphere Model (Bechtel SAIC, 2004a, Table 6.1-1).

Table 2-2. Updated values of the maximal areal biomass, BMAX, standing biomass, BSTAND, and initial biomass, BI.

COMIDA Variable	Plant Product	BMAX and BSTAND (dry kg m^{-2})	BI (dry kg m^{-2})	Comment/Reference
BMAXC BIC BSTAND	Grains	1.13	0.013	Table 7.1-1 in Bechtel SAIC (2004a)
	Leafy vegetables	0.21	0.0021	Table 7.1-1 in Bechtel SAIC (2004a)
	Root crops	0.43	0.0043	From other vegetables entry in Table 7.1-1 in Bechtel SAIC (2004a)
	Fruits	0.62	0.0062	Table 7.1-1 in Bechtel SAIC (2004a)
	Legumes	0.31	0.0031	Based on lima beans in Table 6.52 in in NUREG/CR-5512 Volume 3 (Beyeler et al., 1999). The average yield of snap beans in 0.73 kg/m^2 in the same table.
BMAXP BIP	Pasture	0.476	0.00476	Average from years 1987 to 1996 from Table 6.56 in NUREG/CR–5512 Volume 3 (Beyeler et al., 1999)
BMAXH BIH	Hay	0.476	0.00476	Hay inputs are assumed equivalent to pasture
Per NUREG/CR–6613 (Chanin et al., 1998), it is recommended to set **BSTAND = BMAX** for all five crops (grains, leafy vegetables, roots, fruits, and legumes). The COMIDA2 model defaults BSTAND to be the same BMAX input for pasture and hay.				

2.3.3 Plant Growth Rate (ZKG)

The plant growth rate [1/time units, symbolized as ZKG in Eq. (2-1)] is the rate of plant growth (dry kg/m^2-d) per current biomass (dry kg/m^2). ZKG controls the relative time at which the BMAX or BSTAND plateau is attained after the start of the growing season [Figure 2-5(a)]. The sensitivity of the total dose and the economic cost to this parameter is shown in Figure 2-10.The total cost and the crop disposal area versus ZKG indicate that the individual dose increases with increasing values of ZKG and plateaus at high vales of ZKG. The local maximum in the population dose versus ZKG(grain) arises from the interdiction model. The location of the local maximum coincides with the point at which the crop disposal area versus ZKG(grain) becomes a steeper curve. With increasing interdiction actions, the population dose versus ZKG(grain) becomes a decreasing function, which eventually plateaus at high values of ZKG(grain).

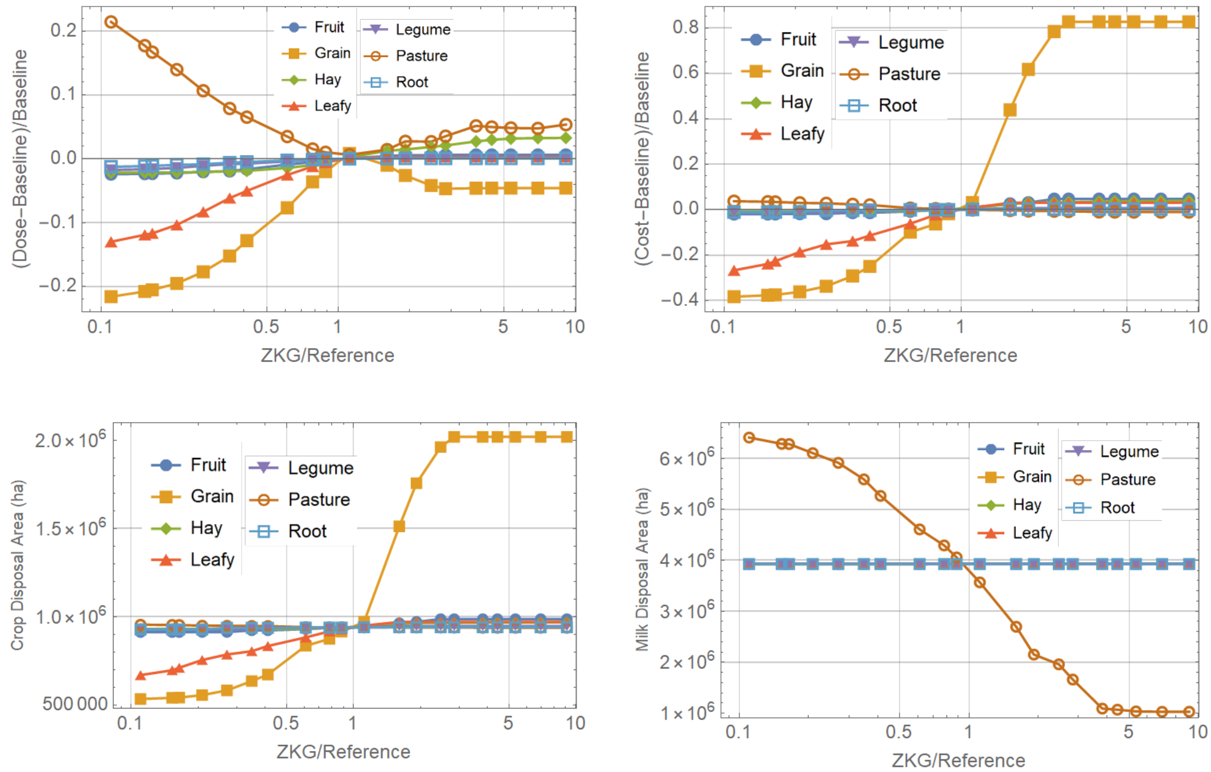


Figure 2-10. Relative change in population dose and economic cost versus the normalized plant growth rate (ZKG), and crop disposal and milk disposal area versus ZKG.

The milk disposal area versus ZKG(pasture) in Figure 2-10 reveals a feature of the COMIDA model: the concentration of radioactivity in milk decreases with increasing ZKG(pasture). This decrease is an artefact of COMIDA model approximations, which disregard continuous growth of pasture during the growing season. Instead, COMIDA assumes that pasture only actively grows during a short period, on the order of 30 days, and then it stops growing and assimilating radioactivity from the soil compartments. In the baseline run, it was assumed ZKG(pasture)=0.306 1/d. Figure 2-11 compares the pasture biomass versus time and versus ZKG. In the baseline run, the pasture biomass curve reaches a plateau after Julian date 150. The rate of contaminant uptake from soil by roots is proportional to the time derivative of the biomass curve. Thus, in the baseline run, assimilation of radioactivity from the soil by pasture practically stops after Julian date 150. Additional uptake of radioactivity would resume only until Julian date 110 of the following year.

Figure 2-11 indicates that the period for active root uptake of contaminants in soil is longer with smaller values of ZKG. This explains why the milk disposal area follows a decreasing trend with increasing ZKG in the lower right plot in Figure 2-10: the contamination in pasture decreases with increasing value of ZKG(pasture). This feature of the COMIDA model should be accounted for in proposing ZKG(pasture) updated inputs.

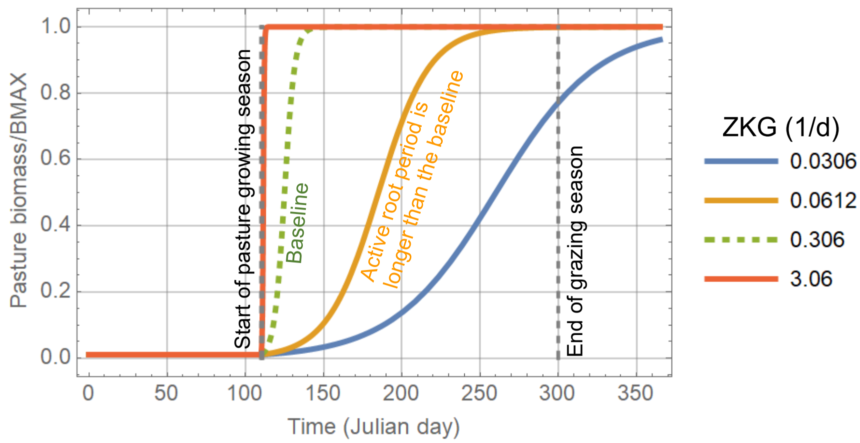


Figure 2-11. Pasture biomass versus time and versus plant growth rate (ZKG)

ZKG Input Parameter Updates

Per the description of the COMIDA model (Abbott and Rood, 1993, 1994), values of ZKG can be computed from estimates of the plant growth time. From the logistic function, Eq. (2-1), if $B(t_o)=B_o$ is a known value of the biomass at time t_o, the growth rate constant can be computed as

$$\mathrm{ZKG} = \frac{1}{t_o}\ln\left(\frac{\frac{\mathrm{BMAX}}{\mathrm{BI}} - 1}{\frac{\mathrm{BMAX}}{B_o} - 1}\right) \tag{2-3}$$

The time t_o is interpreted as the plant growing time, for which there is information in the literature for multiple plant products. It may be assumed that

$$B(t_o) = B_o = 0.99\ \mathrm{BMAX} \tag{2-4}$$

Further, if it is assumed that BI = 0.01 BMAX, then ZKG can be estimated as

$$\mathrm{ZKG} = \frac{1}{t_o}\ln\left(\frac{\frac{1}{0.01} - 1}{\frac{1}{0.99} - 1}\right) = \frac{9.19}{t_o} \tag{2-5}$$

where t_o is the plant growth duration. Updated values of ZKG are listed in Table 2-3, based on information in NUREG/CR-5512, Volume 3 (Beyeler et al., 1999, Table 6.30) and in the report Agricultural and Environmental Input Parameters for the Biosphere Model (Bechtel SAIC, 2004a, Table 6.4-1).

Table 2-3. Growing season duration and updated plant growth rate constant, ZKG

COMIDA Variable	Plant product	Duration (d)	ZKG (1/d)	Comment/Reference
ZKGC	Grains	200	0.046	Bechtel SAIC, 2004a, Table 6.4-1, average present-day climate
	Leafy vegetables	75	0.123	Bechtel SAIC, 2004a, Table 6.4-1, average present-day climate
	Roots	100	0.092	Bechtel SAIC, 2004a, Table 6.4-1, potatoes, present-day climate
	Fruits	160	0.057	Bechtel SAIC, 2004a, Table 6.4-1, average present-day climate
	Legumes	90	0.102	Beyeler et al., 1999, Table 6.30, minimum growing period, other vegetables
ZKGP	Pasture	30	0.306	Beyeler et al., 1999, Table 6.30, minimum growing period, forage. This value was used as input in the baseline run in this report.
		190	0.048	The duration is the assumed duration of the grazing season in the baseline run, to account for the fact that pasture grows continuously during the whole season. See the explanation in the text and in Figure 2-12.
ZKGH	Hay	75	0.123	Bechtel SAIC, 2004a, Table 6.4-1, average present-day climate

For ZKG(pasture), additional considerations are at play. The ZKG values in Table 2-3 are adequate for plant products with discrete harvest dates. For continuously growing and "harvested" pasture, ZKG should also include information on the duration of the growing season (instead of solely the growth duration of a single plant). Otherwise, in the COMIDA model there would not be any incorporation of radioactivity in pasture plant tissues from root uptake for accidents occurring after grass has reached initial maturity (i.e., accidents after day 150 in the baseline case, Figure 2-11). In actuality pasture continuously grows during the grazing season and incorporation of radioactivity into the plant tissues from root uptake could occur at any time during grazing season. Figure 2-12 summarizes an alternative to derive an effective value of ZKG(pasture) allowing for root uptake throughout the grazing season. The ZKG(pasture) can be interpreted as the value associated with an average biomass curve. The blue curves in Figure 2-12 correspond to biomass versus time (ZKG=0.306 1/d) with the start growing time uniformly distributed throughout the grazing season. The red curve is the average biomass curve, which is almost a linear ramp. As currently designed, the COMIDA model does not include a linear ramp function to model plant growth. Alternatively, the value of the effective ZKG may be selected as the best fit of the logistic function [Eq. (2-1)] to the average linear ramp function. The value of the effective ZKG following alternative approach was computed using Eq. (2-5) and t_o=190 days (duration of the grazing season in the baseline case), to yield a value ZKG(pasture)=0.048 1/d. Although such value is the preferred input to the COMDA model, the baseline run considered in this report used ZKG(pasture)=0.306 1/d, to explore implications and sensitivities of the COMIDA model, as designed.

The recommendations summarized as BI=0.01×BMAX, and Eqs. (2-4), and (2-5) are practical recommendations to ensure consistent inputs to the COMIDA2 model, while still allowing flexibility to examine the sensitivity of results to the maximal areal biomass, BMAX, and the duration of the growing season.

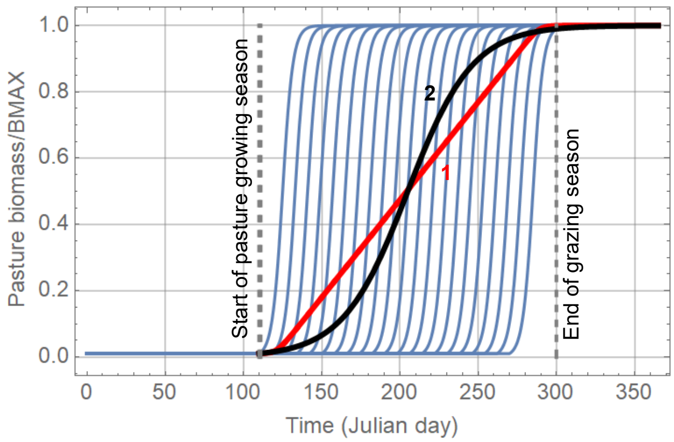


Figure 2-12. Blue curves: pasture biomass versus time with start growth at uniform times during the start and end of the grazing season. Red curve (label 1): average of the blue curves. Black curve (label 2): approximation to the average using a logistic function.

2.3.4 Foliar Interception Constant (ALPHA)

The foliar interception constant, ALPHA [or α in Eq. (2-2)], controls the fraction of deposition on plant surfaces and soil. Figure 2-13 shows the variation in the population dose and economic cost with ALPHA. The economic cost, crop disposal area, and milk disposal area are increasing functions of ALPHA, indicating that the individual dose is an increasing function of ALPHA and eventually plateaus at high values of ALPHA. With increasing values of ALPHA, more fallout is initially deposited on plant surfaces, causing increasing values of individual doses. The population dose versus ZKAB(pasture) exhibits a local maximum and a local minimum, which arise from the interdiction model. The segment between the local maximum and the local minimum in the population dose curve coincide with the domain where the milk disposal versus ALPHA(pasture) curve is steepest: milk interdiction actions help decrease population doses. The population dose increases again at higher values of ALPHA(pasture), where the milk disposal area approaches a plateau. A similar explanation can be provided to rationalize the local maximum in the population dose versus ALPHA(grain) curve. The population dose reaches a local maximum just before the point at which the milk disposal area versus ALPHA(grain) becomes a steeper function.

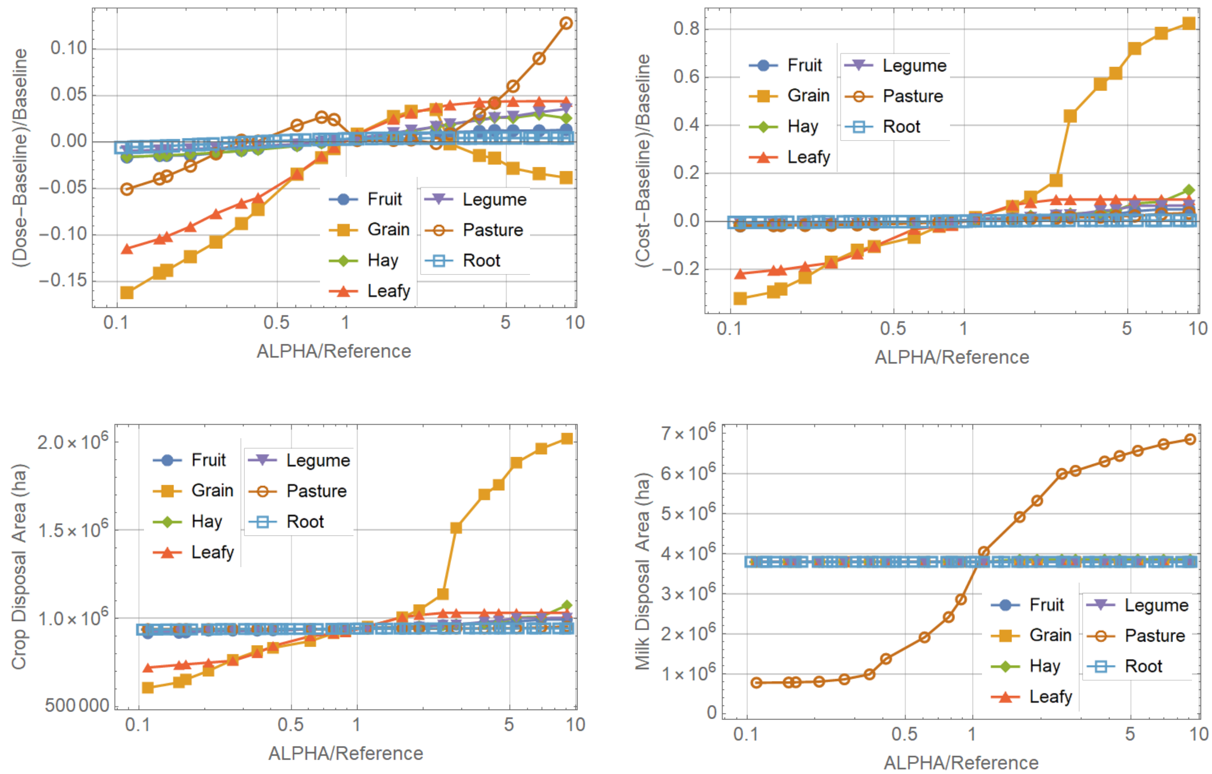


Figure 2-13. Relative change in population dose, economic cost, and milk disposal area versus the normalized foliar interception constant (ALPHA), and crop disposal and milk disposal areas versus ALPHA.

Values of the foliar interception constant parameter, ALPHA, were updated based on IAEA (2010, Tables 4 and 5), which compiles interception fractions for a set of radionuclides, for a variety of vegetables, and under wet deposition or dry deposition. Updated values are listed in Table 2-4

Table 2-4. Updated foliar interception constant, ALPHA (m^2/kg)

Plant product	ALPHA (m^2/kg)	Comment/Reference
Grains	3.5	IAEA, 2010, Table 4, max value for wheat based on wet deposition experiments with Cs (range from 0.5 to 3.5)
Leafy vegetables	7.8	IAEA, 2010, Table 4, median value for Chinese cabbage (range from 3 to 30 m^2/kg)
Roots	9.3	IAEA, 2010, Table 4, median value for radish (range from 5.2 to 16 m^2/kg)
Fruits	3.6	Generic value for fruits not available in IAEA (2010). Value 3.6 m^2/kg is the average interception constant for corn, based on dry deposition of Pu particles (IAEA, 2010, Table 5)
Legumes	1.2	IAEA, 2010, Table 5, mean value for beans, based on dry deposition of Ba, Cs, and Sr, 30 days after sowing
Hay	2.8	Assumed same value as pasture
Pasture	2.8	IAEA, 2010, Table 5, mean values for grass, based on dry deposition of I vapor

2.4 Soil-Plant Transfer Processes

At the fallout event, radionuclides are deposited on plant surfaces and surface soil. As time elapses, radionuclides are transported to the labile soil and deep soil by processes such as percolation and leaching. Surface processes such as resuspension, rainsplash, and weathering change the distribution of radionuclides on surface soil and plant surfaces. Biological processes are modeled in COMIDA as first order transfer rates (i.e., the rate of radionuclide transfer is proportional to the mass or concentration in a plant or soil compartment). Plants may decay and die, and their radionuclide inventory can be returned to surface soil (process referred to as senescence). Figure 2-1 is a schematic summarizing the physical and biological transport processes. The COMIDA model is a dynamic mass balance model among five compartments (compartments representing surface soil, labile soil, fixed soil, vegetable surface, and vegetable internals). Tillage is accounted for to uniformly redistribute contaminants in the surface soil layer and labile soil layer according to their soil masses. At the time of harvest, inventory is removed from the "vegetable internals" compartment, and the harvested inventory is separately tracked in a storage compartment to compute radionuclide concentrations in foodstuffs. On the other hand, removal of inventory by grazing is conservatively ignored (i.e., grazing is assumed not to remove radionuclide inventory from the pasture compartment).

2.4.1 Surface Soil Bulk Density (PSS), Root Soil Bulk Density (PSR), Thickness of Root Zone Soil (XR), and Thickness of Surface Soil (XS)

Soil parameters (soil density and thickness) to describe the root zone and surface soil are applied to cultivated cropland to calculate the redistribution of contaminants after cropland tilling. At the time of tilling, radionuclides in the surface soil and labile soil compartments are uniformly distributed. Accordingly, after tilling the mass of radionuclides in the corresponding soil compartment is proportional to the product density × thickness. In addition, the product density × thickness of the labile soil compartment is used to compute the rate of root uptake. Increasing the labile soil mass per unit of area decreases the rate of root uptake, and vice versa.

Input values to the COMIDA2 model through the WinMACCS interface require one set of values of soil density and thickness for all plant products. The labile soil thickness is plant type dependent; therefore, the single labile soil thickness input to comida is interpreted to be an average value over all plant types. The WinMACCS interface imposes a restriction on the surface soil density in that it must not exceed 1,000 kg/m^3 (the labile soil density, on the other hand, is not restricted). WinMACCS displays an error message when trying to input a value exceeding 1,000 kg/m^3 and forbids execution of the run. It appears that such restriction is a coding error in WinMACCS Version 3.11.2; however, this error is not critical and there are workarounds, discussed later in this section.

Figure 2-14 displays the sensitivity of the population dose and economic cost to the soil parameters. For the sensitivity analysis, the surface soil density (PSS) was varied from 500 to 1,000 kg/m^3, and the root soil density from 500 to 5,000 kg/m^3. The curves for root soil density and root soil thickness perfectly overlap in Figure 2-14. The curves associated with surface soil density and surface soil thickness also overlap (the orange squares are only plotted to the left of 1, because WinMACCS constrains surface soil densities to be less or equal than 1,000 kg/m^3; 1,000 kg/m^3 was the reference surface soil density in the baseline run). The curves overlap because the equations implemented in the COMIDA model depend on the product (soil density)×(soil thickness); therefore, varying any of the factors of the product has an equivalent effect on population dose and economic cost. The population dose and economic cost mostly decrease with increasing values of the soil parameters. The individual dose

decreases with increasing product (soil density)×(soil thickness) [e.g., Abbott and Rood, 1993, Equations (10) and (14)] causing a decreasing trend in the population dose, in case of constant interdiction actions. The economic cost is highly controlled by the crop disposal area (lower plot in Figure 2-14).

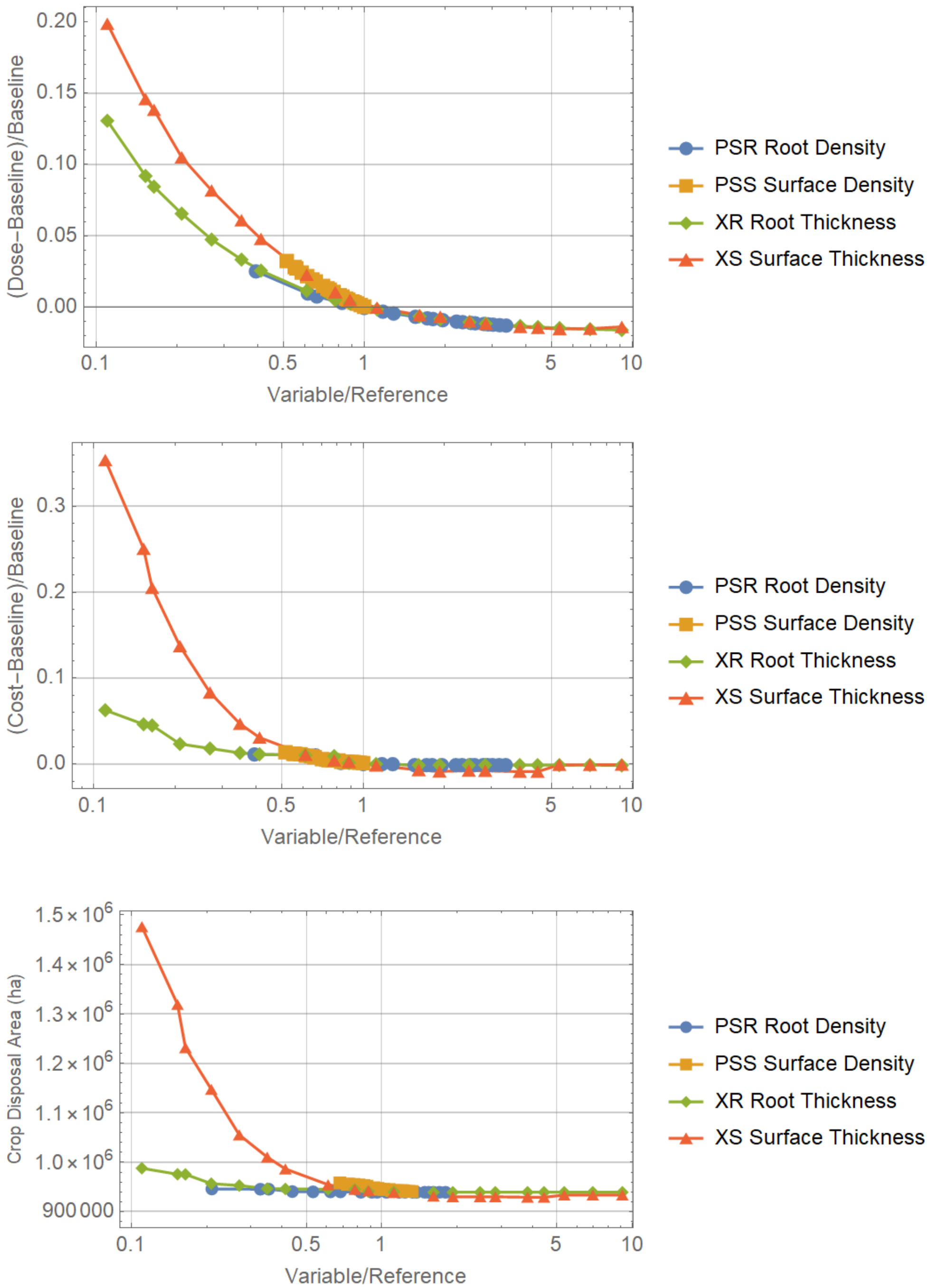


Figure 2-14. Relative change in population dose and economic cost versus the normalized soil parameters (density PSR, PSS, and thickness XR, XS), and crop disposal area versus soil parameters.

It is noted that the soil thicknesses were varied over two orders of magnitude to examine the mathematical sensitivity of the COMIDA2 model to these inputs; however, thicknesses have much narrow range of physical variability. At small surface soil thicknesses, the contaminant concentration in soil becomes very high.

Updates from IAEA (2016) and SNL (2007), are included in Table 2-5. A reasonable value of the soil density is 1,400 kg/m^3. The range of variability of the density is relatively narrow, and the sensitivity of the COMIDA model is minor to negligible over such small physical range of variability of the soil density. Given the WinMACCS constraint on the surface soil density, the input soil density is set to 1,000 kg/m^3, but the input surface soil thickness is adjusted to attain a desired density × thickness product. Values of the soil thickness are recommended slightly biased towards low values (0.1 m for the root soil and 0.001 m for the surface soil). The surface soil thickness was adjusted to a value equal to 0.0014 m to attain a target product density × thickness equal to 1.4 kg/m^2, to approximately correct for the WinMACCS constraint on the surface soil density.

Table 2-5. Soil characteristic parameters, density (PSR, PSS) and thickness (XR, XS)

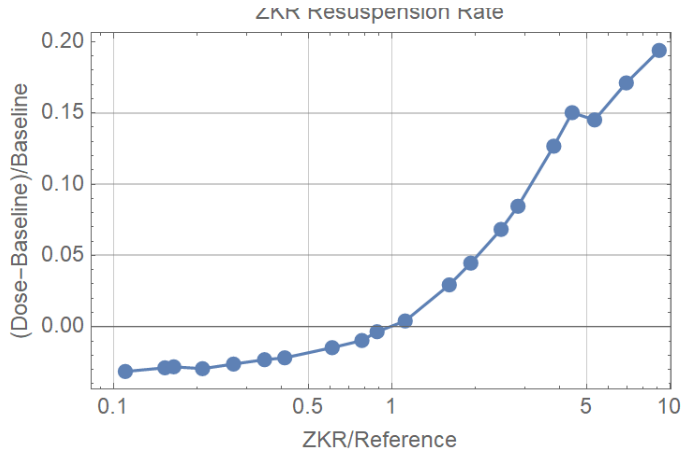
Parameter	Value	Comment/Reference
PSR, root or labile soil density.	1,400 kg/m^3	The bulk soil density ranges from 1,300 to 1,500 kg/m^3, depending on the type of soil. For example, sand soil: 1,500 kg/m^3; loam soil: 1,420 kg/m^3; clay soil: 1,300 kg/m^3; organic soil: 1,350 kg/m3 (IAEA 2016, Table 25); all soil: 1,500 kg/m^3 (SNL, 2007, Table 6.6-3). Over such narrow range of variability of the bulk density, the COMIDA model exhibits minimal to negligible dependence. A reference value of 1,400 kg/m^3 is a reasonable value in general.
XR, root or labile soil thickness	0.1 m	The root zone of crops commonly extends few tens of centimeters. For example, the pasture soil layer is on the order of 0.1 m (IAEA, 2016, Table 25). The arable soil thickness for crops is on the order of 0.25 m (IAEA, 2016, Table 25; SNL, 2007, Table 6.6-3). A single value is used in the COMIDA model for all plant products (crops, pasture, and hay). The COMIDA model exhibits minimal to negligible dependence on the outputs over such narrow range of variability of the soil thickness. A value equal to 0.1 m is reasonable and slightly conservative for population dose estimates.
PSS, surface soil density	1,000 kg/m^3	A value equal to PSR (=1,400 kg/m^3) is recommended. However, the WinMACCS interface restricts this input to a maximum value of 1,000 kg/m^3. The COMIDA model explicitly implements equations that depend on the product density × thickness. Corrections to the density are applied to surface soil thickness.
XS, surface soil thickness	0.0014 m	A value equal to 0.001 is recommended. However, the thickness is slightly adjusted, from 0.001 to 0.0014 m, to address an unexplained restriction of the WinMACCS interface on the surface soil density (see the previous entry; the COMIDA equations depend on the product soil density × soil thickness). The thickness of the soil layer subject to resuspension is only few millimeters (SNL, 2007, Table 6.6-3). Selecting a low value of the range of variability is slightly conservative for population dose and economic cost estimates.

2.4.2 Resuspension Rate Constant (ZKR)

The resuspension rate constant, ZKR, in units of 1/time, is the rate of resuspension of contaminants from the surface soil to deposit on vegetation surfaces. ZKR is calculated as the product of a resuspension factor (in units of 1/length) and the deposition velocity (in units of length/time) (Sutter, 1982). IAEA (2009, Table 1) lists resuspension factors and corresponding measured locations. Resuspension factors in the days and months following an accident were concluded to be on the order of 10^{-5} m^{-1} in residential areas on a site undergoing cleanup operations or on an arid site; and 10^{-6} m^{-1} on a rural site. The resuspension factor decreased to values on the order of 10^{-8} m^{-1} to 10^{-9} m^{-1}, after 3 to 4 years of the accident. For deposition velocities, Table 6-35 in Bechtel SAIC (2004b) provides various references dating from 1993 to 2001. The RESRAD code user guide considers deposition velocities equal to 0 m/s for gaseous elements, 0.01 m/s for halogens, and 0.001 m/s for all other elements (Yu et al., 2001). The IAEA rural resuspension factor (10^{-6} m^{-1}) is relevant to the COMIDA2 model (which accounts for farmland activities), as well as the RESRAD other-elements deposition velocity (0.001 m/s), from which a value equal to 10^{-9} s^{-1} ($=10^{-6}$ $m^{-1}\times0.001$ m/s) is derived. However, IAEA (2009) cites higher resuspension factors (up to 10^{-5} m^{-1} in residential areas), and a value equal to 10^{-8} s^{-1} ($=10^{-5}$ $m^{-1}\times0.001$ m/s) or 8.64×10^{-4} d^{-1} is recommended as ZKR input, to account for some uncertainty in the resuspension factor.

A single value of ZKR is used in COMIDA2 for all of the plant products. Figure 2-15 shows the sensitivity of the dose and cost on the resuspension rate, around the baseline value. Both the dose and cost monotonically increase with increasing values of the resuspension rate.

In summary an updated value ZKR = 8.64×10^{-4} d^{-1} is recommended, based on information in IAEA (2009, Table 1) and the RESRAD user guide (Yu et al., 2001).



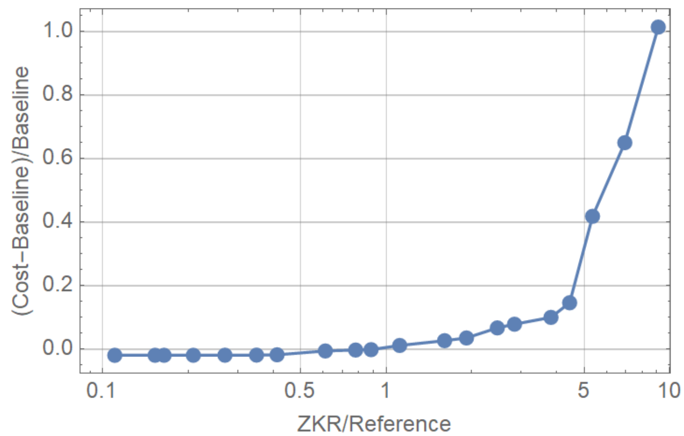


Figure 2-15. Relative change in population dose and economic cost versus the normalized resuspension rate (ZKR).

2.4.3 Rainsplash Rate Constant (ZKRS)

The rainsplash rate constant, ZKRS, is the rate of contamination movement from the surface soil to plant surfaces due to rain impacting the soil. The mobilization is equivalent to the effect of resuspension. In the COMIDA model, rainsplash increases the contamination level of plant surfaces. Dreicer et al. (1984) considered ZKRS values equal to 8.6×10^{-4} d^{-1} for “semiarid locations” and 10^{-9} d^{-1} (arbitrarily small value) for “temperate climates not characterized by intense rainstorms.” The rainsplash rate is dependent on crops height (e.g., different height of lettuce versus corn). In the COMIDA model, the rainsplash rate is an effective value balancing plant deposition of contaminants from soil with removal of deposits by the rain. NUREG/CR–5512 Volume 3 (Beyeler et al., 1999) states that the importance of rainsplash is related to the type of crop, soil properties, and intensity of the rainfall events. Under some circumstances, the amount of contaminated material mobilized by rainsplash may equal or even exceed deposition on the plant by other mechanisms. IAEA (2003) concluded, as part of the parameter evaluation of biosphere models (BIOMASS), that rainsplash was not a relevant process in dose modeling. NUREG/CR–6825 (PNNL, 2003) also noted that rainsplash component is frequently justifiably neglected in dose models. Given these views it is recommended that ZKRS be assigned a value of 0, to dismiss contributions from rainsplash to the plant surface loading.

Figure 2-16 shows the relative variation of the population dose and economic cost with rainsplash, as implemented in the COMIDA model. The dose and the cost are increasing functions (almost linear functions) of the rainsplash, as modeled in COMIDA. For the sensitivity plot, ZKRS was varied from 10^{-5} to 10^{-3} 1/day. The reference was set as 10^{-5} 1/day, which produced similar results to the baseline run with ZKRS=0.

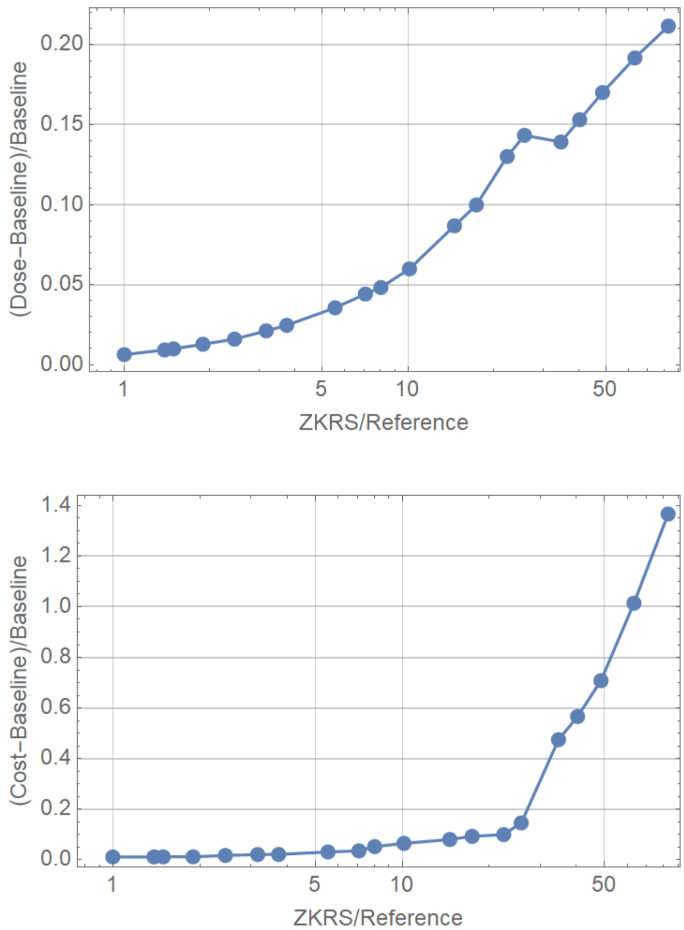


Figure 2-16. Relative change in population dose and economic cost versus the normalized rainsplash rate (ZKRS).

The effect of the rainsplash, as modeled in COMIDA, is mathematically equivalent to the effect of resuspension. To prove this point, Figure 2-17 shows the total dose versus ZKR + ZKRS. The figure overlaps results obtained by varying solely ZRS or ZKRS. Identical results were obtained with identical values of ZKR + ZKRS, independently of the individual values of ZKR or ZKRS. Similar results are obtained with other outputs of the MACCS code, including the total economic cost. Therefore, ZKR and ZKRS are mathematically equivalent as modeled in COMIDA.

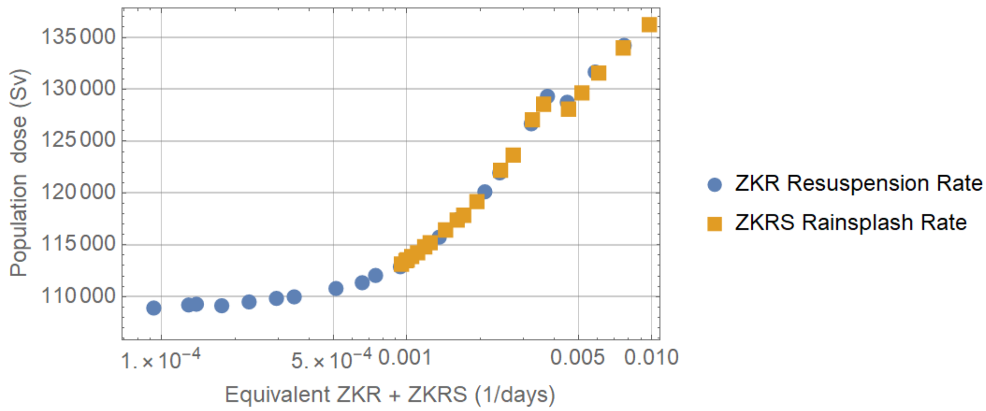


Figure 2-17. Population dose versus (ZKR + ZKRS). The plot shows results varying solely ZKR (blue circles) or ZKRS (orange squares). The results are identical for identical values of ZKR+ZKRS.

In summary, based on findings by IAEA (2003) and NUREG/CR–6825 (PNNL, 2003), it is recommended to disable contributions to plant surface loading of contaminants arising from rainsplash (i.e., ZKRS = 0 1/d). ZKRS is mathematically redundant with the resuspension rate constant, ZKR. The user may apply corrections to the resuspension rate constant to account for rainsplash, if needed.

2.4.4 Percolation Rate Constant (ZKP)

The percolation rate constant, ZKP, controls the rate of transfer from the surface soil to the root zone or the labile soil due to water movement. Percolation reduces the amount of contamination on the surface. The recommended value for ZKP in NUREG/CR–6613 (Chanin et al., 1998) is 2×10^{-2} d^{-1} for sites in the western U.S. (based on Langham, 1972; Anspaugh et al., 1975) and 2×10^{-3} d^{-1} for other locations (IAEA, 1992). The COMIDA model assumes that the rate of radioactivity transfer from the surface soil compartment to the labile soil compartment due to water movement is proportional to the product of ZKP and the radioactivity present in the surface soil compartment (Abbot and Rood, 1993, 1994); (i.e., radioactivity transfer due to water movement is modeled as a first order process). It is highlighted that ZKP depends on water fluxes and the assumed thickness and water content of the surface soil layer, absorption to soil, and the soil hydraulic conductivity. Solubility constraints of radionuclide-bearing mineral phases may also slow down radionuclide mobilization. COMIDA requires a single value of ZKP for all plant products and all radionuclides. Thus, ZKP is an average, lumped parameter, synthetizing and approximating several processes (water flows, soil retardation, and chemical reactions and complexation of fallout with surface soil minerals).

The percolation rate constant differs from another COMIDA input, referred to as the leach rate constant (ZKL) in that this latter explicitly takes into account radionuclide sorption to soil, although it also ignores the solubility of mineral phases. The COMIDA model ignores variability among the different plant products (associated, for example, different irrigation rates). Average values for the percolation rate constant, ZKP, must be input that are applicable to all plant products and all radionuclides.

Figure 2-18 shows that both the population dose and economic cost are decreasing functions of the percolation rate.

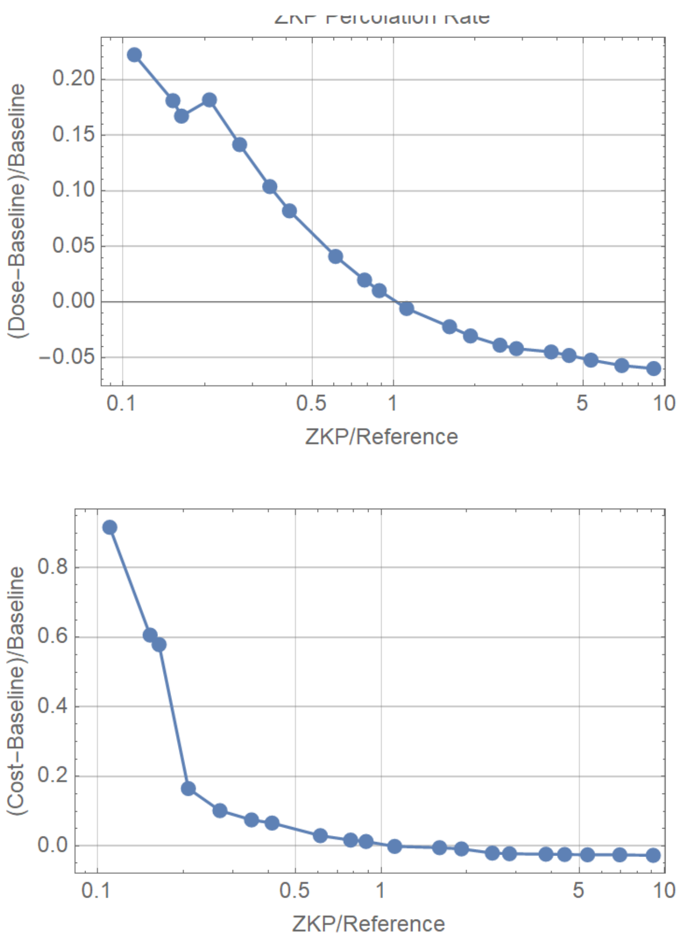


Figure 2-18. Relative change in population dose and economic cost versus the normalized percolation rate (ZKP).

To propose values of ZKP, it was examined a derivation based only on a water balance [ZKP = water flux/(water content in soil × soil thickness)], considering 1 m/yr for water flux, 0.25 for the water content, and 1 mm for soil thickness, and a value equal to 10.9 1/d was computed, which corresponds to a half-depletion time equal to 0.06 days or approximately 1.5 hours. Such short depletion time would tend to reduce dose and cost estimates (Figure 2-18). Instead, the ZKP values in NUREG/CR–6613 (Chanin et al., 1998) disregarded active irrigation and considered only declines in resuspension at Chernobyl (IAEA, 1992) (indicating half-depletion times from 0.5 years to 2 years) as well as the PATHWAY model data based on a half-depletion time equal to 35 days for western US semiarid areas. Ignoring active irrigation is conservative for individual dose estimates, and it is recommended to adopt an input value ZKP= $2{\times}10^{-2}$ d^{-1} in general (equivalent to approximately a 35-day half-depletion time). NUREG/CR–6613 (Chanin et al., 1998) includes a lower value ($2{\times}10^{-3}$ d^{-1}) for sites other than the western US; however, such lower value is too unrealistic regarding water irrigation needs to grow plant products in the context of the simplified linear transfer rates modeled in COMIDA.

2.4.5 Weathering Rate Constant (ZKW)

In the COMIDA model, contaminant removal from the vegetation (and deposited on surface soil) from weather processes is modeled as a first-order removal model (Miller and Hoffman, 1983), based on a weathering half-life, T (days), or a weathering rate constant, ZKW (days^{-1}) defined as:

$$\mathrm{ZKW} = \frac{\ln(2)}{T} \tag{2-6}$$

COMIDA models the weathering action as a rate of removal of contaminants from plant surfaces, deposited back on surface soil. In other words, the radionuclide mass is transferred to the surface soil compartment by the weathering process, and from the surface soil contamination is subject to resuspension, transfer to the root soil, or direct ingestion by grazing animals. The NUREG/CR–6613 value for the weathering rate constant is 4.95×10^{-2} d^{-1} (equivalent to 14-day weathering half-life) (Chanin et al., 1998). The COMIDA model requires a single input for all plant products; therefore, the weathering rate constant is interpreted as an average parameter over all plant products. Other biosphere models also consider characteristic times on the order of 14 days for weathering (Table 6-37 in Bechtel SAIC, 2004b). Crop-specific weathering rates are available in the literature. Smith et al. (1996, p. 5-30), for example, treated individual weathering rates for different crops.

Due to the design of the COMIDA model, the foliar absorption rate constant (Section 2.4.6) is correlated to the weathering rate constant. Independently decreasing the weathering rate may increase the foliar absorption uptake to values exceeding experimental uptake proportions; the weathering rate and the foliar absorption rate constant must be jointly adjusted to enforce physical restrictions and ensure consistency of the COMIDA model outputs (see Section 2.4.6). However, for the sensitivity analysis the weathering rate and the foliar absorption rate constant were independently varied. Figure 2-19 shows the mathematical sensitivity of the population dose and the economic cost to variation in weathering rates alone (ignoring any relationship to the foliar absorption rate constant). The individual dose is a decreasing function of the weathering rate, because weathering removes contaminants from plant surfaces (radioactivity becomes incorporated in plant tissues by translocation). The economic cost follows the decreasing trend of the individual dose. The local maximum in the population dose is an effect of the interdiction model. At low values of ZKW the extent of the crop disposal area is high, which controls the population dose, and cause the increasing trend in the population dose at low values of ZKW.

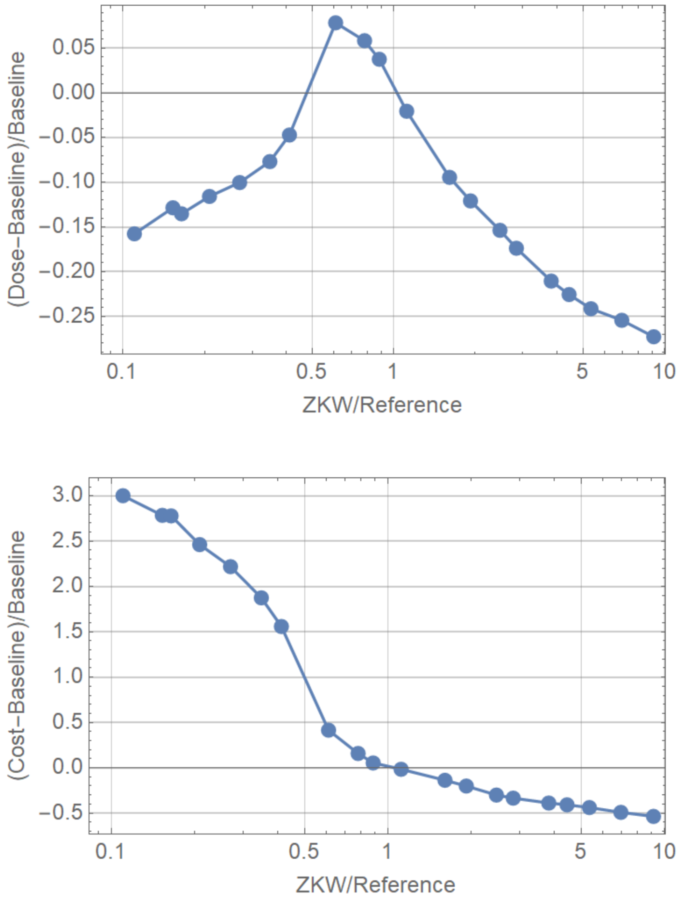


Figure 2-19. Relative change in population dose and economic cost versus normalized weathering rates (ZKW).

The 14-day weathering half-life is a reasonable value; and a value ZKW = 4.95×10^{-2} 1/d is considered adequate for general use, in consistency with information in NUREG/CR–5512, Volume 3 (Beyeler et al., 1999), NUREG/CR–6613 (Chanin et al., 1998), and IAEA (2016). Multiple studies on different plant products (cereals, grass, fruits) indicate half-life weathering times ranging from 10 to 50 days, considering elements such as Cs, I, Pu, and Sr and fallout from the Chernoby accident (e.g., Lim et al., 2001; Kirchner, 1994; Ishida et al., 1988; Monte, 1991; Assimakopoulos et al., 1988; Ohmomo et al., 1991; Pinder and Doswell, 1985), and the selected 14-day weathering half-life falls within weathering rates indicated by these studies. However, it is noted that the foliar absorption rate constant (ZKAB, Section 2.4.6) is selected so that foliar absorption in competition with weathering cause incorporation of surface contamination into plant tissues to be controlled by the translocation factor (denoted as fa in Section 2.4.6). Therefore, in the COMIDA model, the weathering rate plays a secondary role: it is mainly used to define a foliar absorption rate constant. The total amount of plant surface fallout that is incorporated into plant tissues is mostly controlled by the translocation factor considered in the COMIDA model, and not by the weathering rate. Again, a value ZKW = 4.95×10^{-2} 1/d is regarded adequate for general use, provided the foliar absorption rate constant, ZKAB, is defined as recommended in Section 2.4.6.

2.4.6 Foliar Absorption Rate Constant (ZKAB)

The foliar absorption rate constant is the rate of incorporation of radioactivity in plant tissues from radioactivity deposited on plant surfaces, in units of 1/time. The foliar absorption rate constant is related to the more commonly used term translocation factor in the health physics literature. Translocation is the process in which chemical elements, which have been deposited on the leaf surface of the plant, move from the leaf surface to the edible parts of the plant. Other common equivalent terms are foliar contamination, foliar uptake, and foliar deposition. Translocation in general is the transport of radionuclides within the plant subsequent to foliar uptake.

Experimental information related to foliar translocation is commonly reported as a steady-state ratio (dimensionless translocation factor symbolized as fa) of radioactivity in the edible plant to the radioactivity on the plant surface. Information is scarce on kinetic transfer of plant surfaces to plant tissues (which is the input required by the COMIDA model).

For the PATHWAY model, Whicker and Kirchner (1987) recognized the lack of data to define dynamic transfer rates, and approximated the foliar absorption rate constant as

$$\mathrm{ZKAB} = \frac{fa}{1-fa} Kw \tag{2-7}$$

where
fa — translocation factor, fraction of surface contamination absorbed by plant
Kw — weathering rate constant (= ZKW, Section 2.4.5)

Whicker and Kirchner (1987) expressed the foliar absorption rate constant as a function of the weathering rate (=ZKW, Section 2.4.5) to ensure foliar uptake in a proportion consistent with the experimental translocation factor, when absorption and weathering are in competition for removal of plant surface contamination. A simple example is presented to explain the long-term proportion of foliar uptake predicted by Eq. (2-7), and the connection to experimental values of the translocation factor, fa. Consider a case with two compartments, vegetable internals and vegetable surface, not exchanging mass with any other compartment, and ignore radioactive decay, and consider foliar absorption and weathering as the only mass transfer mechanisms. The mass conservation equation for the vegetable surface compartment for such system is

$$\frac{d\,m_s}{dt} = -(\text{weathering} + \text{absorption}) = -K_w\,m_s - \mathrm{ZKAB}\,m_s = -\frac{K_w}{1-fa} m_s \tag{2-8}$$

where m_s is the mass on the plant surface. The solution to Eq. (2-8) is an exponential decay function

$$m_s(t) = m_o e^{-\frac{K_w}{1-fa}t} \tag{2-9}$$

m_o is the initial fallout mass deposited on plant surfaces. The absorbed mass, m_a, as a function of time is determined by solving the following equation, with $m_a(t=0)=0$ as the initial condition:

$$\frac{d\, m_a}{dt} = \mathrm{ZKAB}\; m_s = \frac{fa\, K_w}{1 - fa} m_o e^{-\frac{K_w}{1-fa}t} \tag{2-10}$$

which solution is

$$m_a(t) = fa\, m_o \left(1 - e^{-\frac{K_w}{1-fa}t}\right) \tag{2-11}$$

In the limit when the time is large ($t \to \infty$), m_a=$fa\ m_o$, which is the expected amount of mass absorption for a foliar translocation factor equal to fa. Therefore, defining the foliar absorption rate constant as in Eq. (2-7) (with Kw =ZKW; Section 2.4.5) is designed to produce a foliar absorption ratio equal to fa, when weathering and foliar uptake compete for removal of plant surface contamination. If weathering was set ZKW = 0 and ZKAB was independently set to a finite value, such combination could lead to a foliar uptake well in excess of the experimental foliar translocation factor. The input ZKAB value must be consistent with the ZKW input. ZKAB may be input by the user independently of ZKW if kinetic absorption rates were experimentally known, which is uncommon. For a future update to the WinMACCS interface or to the COMIDA2 model, it is recommended to require the foliar translocation factor, fa (per element and per plant product) as input and internally compute ZKAB using Eq. (2-7).

Figure 2-20 displays the relative change in population dose and economic cost versus the normalized foliar absorption rate. Radionuclide-dependent values were correlated using the rank-correlation WinMACCS function. The individual dose is an increasing function of ZKAB, accordingly the economic cost is an increasing function of ZKAB. Under relatively constant interdiction actions, the population dose is also an increasing function of ZKAB. The decreasing trend in the population dose versus ZKAB(pasture) and the up-and-down trend versus ZKAB(grain) are consequence of the interdiction model. Figure 2-20 also includes plots of the crop disposal and milk disposal areas versus ZKAB. The economic cost is strongly correlated to the crop disposal area. The increasing trend in the milk disposal area versus ZKAB(pasture) explains the decreasing population dose versus the same variable. The increasing trend in the population dose versus ZKAB(grain) corresponds to a range of ZKAB where interdiction actions show minor variability. At high values of ZKAB(grain) (> baseline value), interdiction actions significantly increase causing the total dose to decrease with increasing values of ZKAB(grain).

For leafy vegetables, hay, and pasture, the baseline ZKAB input values were selected so that the dominant proportion of fallout on plant surfaces would be assimilated in the plant tissues. As such, further increases in ZKAB have minor effects on the population dose and the economic cost. For grain, the baseline ZKAB corresponds to a relatively small proportion of surface contamination translocation, and the population cost and economic cost are expected to exhibit more variability with variation in ZKAB(grain). The input baseline values are discussed in the following paragraphs.

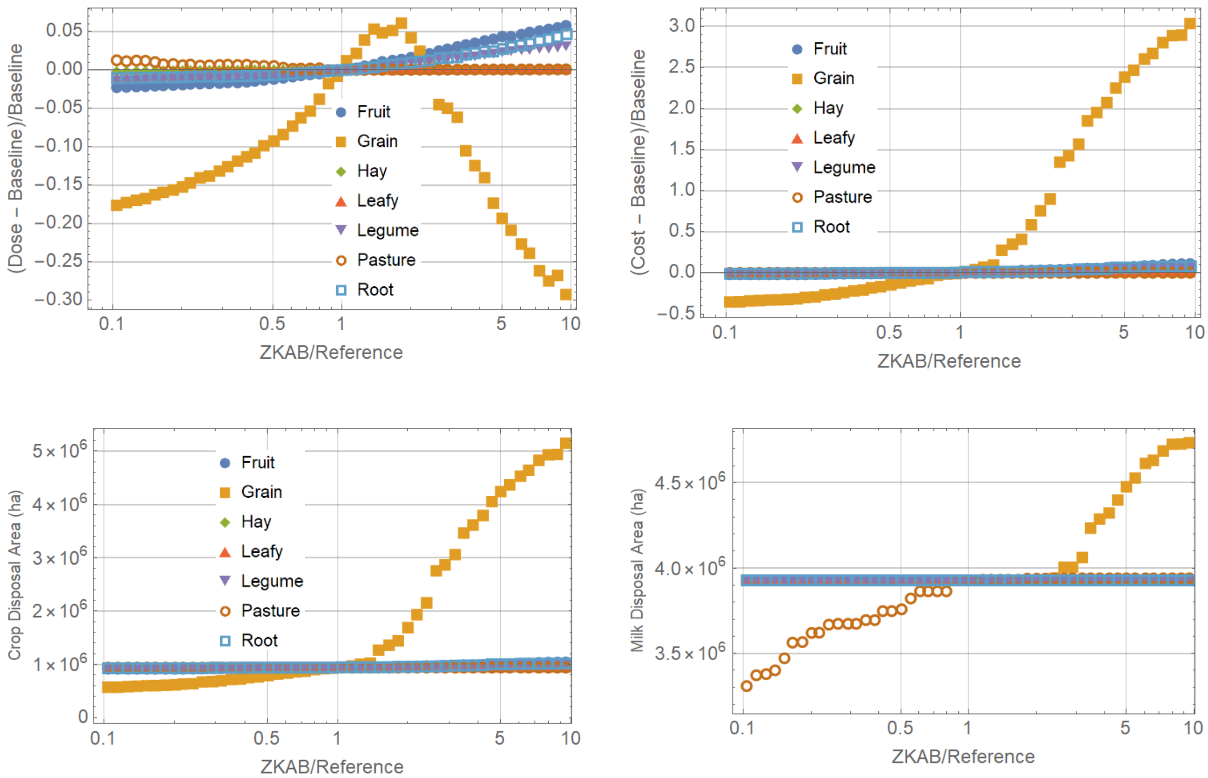


Figure 2-20. Relative change in population dose and economic cost versus the normalized foliar absorption rate (ZKAB), and crop disposal area and milk disposal area versus ZKAB.

Translocation rate constants, *fa*, from several publications were compiled by IAEA (2009, Translocation chapter, p. 49; 2016, Table 23). The report Environmental Transport Input Parameters for the Biosphere Model (Bechtel SAIC, 2004b, Table 4-4, Table 6-36) includes an alternative compilation of translocation factors, from sources dating from 1983 to 2001. Relevant translocation factors for elements tracked in the baseline input are listed in Table 2-6. For several entries in Table 2-6, a conservative input equal to 0.99 (bold font) was assumed when information for the specific element and plant product was lacking. Other entries with a value equal to 0.99 correspond to conservative recommendations in the literature with *fa*=1. Instead of 100 percent translocation, it is suggested to use *fa*=0.99 in Eq. (2-7) (i.e., it is assumed that 99 percent of the initial plant surface fallout is incorporated into plant tissues by translocation; the remaining 1 percent may be transferred to surface soil by weathering). For pasture, Section 2.5.2 explains that the COMIDA model underestimates the grass root uptake of radioactivity; thus, selection of high values of *fa* for pasture is justifiable to address limitations of the COMIDA model.

Table 2-7 lists the computed values of the foliar absorption constant, ZKAB, based on the translocation factors in Table 2-6, the assumed value of the weathering rate constant ZKW=4.95×10^{-2} 1/d (Section 2.4.6), and Eq. (2-7).

Table 2-6. Translocation factors, *fa*

Element	Grain	Leafy	Roots	Fruits	Legume	Pasture	Hay	Comment/Reference
Am	0.005	0.99	0.29	0.0033	0.0033	0.99	0.99	Grains: IAEA, 2016, Table 23. Roots: Smith et al., 1996, Table 5-17. Leafy vegetable: IAEA, 2016, Table 23; and Bechtel, 2004b, Table 6-36, entry 7. Fruits: IAEA, 2016, Table 23 [IAEA, 2009, Translocation, Table 6, geometric mean=5×10^{-6}). Legume: assumed value based on fruits. Pasture & Hay: IAEA, 2016, Table 23 (grass); and Bechtel, 2004b, Table 6-36, entry 7
Ba	0.027	**0.99**	0.022	0.016	0.016	**0.99**	**0.99**	Grains: IAEA, 2009, Translocation, Table 4 (max). Roots: IAEA, 2009, Translocation, Table 5 (geometric mean). Fruits: IAEA, 2009, Translocation, Table 6 (max). Legume: assumed value based on fruits.
Ce	0.078	**0.99**	0.078	0.078	0.078	**0.99**	**0.99**	Grains: IAEA, 2009, Translocation, Table 4, grain growth (max). Roots, fruits, and legumes: assumed value based on grains.
Cm	0.085	**0.99**	0.016	0.121	0.121	**0.99**	**0.99**	Assumed Sr values for grains, roots, and fruits, per NUREG/CR–6613 (Chanin et al., 1998, Volume 2, Table A-5)
Cs	0.27	0.99	0.13	0.29	0.29	0.99	0.99	Grains: IAEA, 2009, Translocation, Table 2, grain growth stage (max). Leafy vegetable: IAEA, 2016, Table 23; and Bechtel, 2004b, Table 6-36, entry 7. Roots: IAEA, 2009, Translocation, Table 5 (max). Fruits: IAEA, 2009, Translocation, Table 6 (max). Legume: assumed value based on fruits. Pasture & Hay: IAEA, 2016, Table 23 (grass); and Bechtel, 2004b, Table 6-36, entry 7.
I	0.09	0.99	0.1	0.1	0.1	0.99	0.99	Grains: IAEA, 2016, Table 23. Leafy vegetable: IAEA, 2016, Table 23; and Bechtel, 2004b, Table 6-36, entry 7. Fruit, roots: IAEA, 2016, Table 23, potato. Legume: assumed value based on fruits. Pasture & Hay: IAEA, 2016, Table 23 (grass); and Bechtel, 2004b, Table 6-36, entry 7.
La	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	**0.99**	Assumed values
Pu	0.005	0.99	0	0.0033	0.0033	0.99	0.99	Grains: IAEA, 2016, Table 23. Leafy vegetable: IAEA, 2016, Table 23; and Bechtel, 2004b, Table 6-36, entry 7. Roots: IAEA, 2016, Table 23, potato. Fruits: IAEA, 2016, Table 23 [IAEA, 2009, Translocation, Table 6, geometric mean=3×10^{-6}]. Legume: assumed value based on fruits. Pasture & Hay: IAEA, 2016, Table 23 (grass); and Bechtel, 2004b, Table 6-36, entry 7.
Ru	0.012	**0.99**	0.012	0.012	0.012	**0.99**	**0.99**	Grains: IAEA, 2009, Translocation, Table 4 (max). Roots, fruits, and legumes: assumed value based on grains.
Sr	0.085	**0.99**	0.016	0.121	0.121	**0.99**	**0.99**	Grains: IAEA, 2009, Translocation, Table 3, grain growth stage (max). Roots: IAEA, 2009, Translocation, Table 5 (max). Fruits: IAEA, 2009, Translocation, Table 6 (max). Legume: assumed value based on fruits.
Te	0.27	**0.99**	0.008	0.29	0.29	**0.99**	**0.99**	Assumed Cs values for grains and fruits, per NUREG/CR–6613 (Chanin et al., 1998, Volume 2, Table A-5). Roots: IAEA, 2009, Translocation, Table 5 (geometric mean). Legume: assumed value based on fruits.

Note: The value **0.99** is a conservative assumption, in the absence of element-specific and crop-specific information. Other 0.99 values (non-bold), were selected in consistency with IAEA (2016, Table 23) and Bechtel (2004b, Table 6-36, Entry 7) recommending values equal to 1 for leafy vegetables, grass, and fresh forage. A value *fa*=0.99 is adopted, instead of 1, to avoid division by zero in Eq. (2-7).

Table 2-7. Updated foliar absorption rate constant, ZKAB (1/d), considering ZKW=4.95×10^{-2} 1/d (Section 2.4.6), fa values in Table 2-6, and Eq. (2-7)

Element	Grains	Leafy	Roots	Fruits	Legume	Pasture	Hay
Am	2.49E-04	4.90	0.020	1.64E-04	1.64E-04	4.90	4.90
Ba	1.37E-03	4.90	1.11E-03	8.05E-04	8.05E-04	4.90	4.90
Ce	4.19E-03	4.90	4.19E-03	4.19E-03	4.19E-03	4.90	4.90
Cm	4.60E-03	4.90	8.05E-04	6.81E-03	6.81E-03	4.90	4.90
Cs	1.83E-02	4.90	7.40E-03	2.02E-02	2.02E-02	4.90	4.90
I	4.90E-03	4.90	5.50E-03	5.50E-03	5.50E-03	4.90	4.90
La	4.90	4.90	4.90	4.90	4.90	4.90	4.90
Pu	2.49E-04	4.90	0	1.64E-04	1.64E-04	4.90	4.90
Ru	6.01E-04	4.90	6.01E-04	6.01E-04	6.01E-04	4.90	4.90
Sr	4.60E-03	4.90	8.05E-04	6.81E-03	6.81E-03	4.90	4.90
Te	1.83E-02	4.90	3.99E-04	2.02E-02	2.02E-02	4.90	4.90

2.4.7 Senescence Rate Constant (ZSEN)

Senescence is the process of plant aging and reincorporation of inventory assimilated in the plant tissues back to soil. The senescence rate is the rate of return of internally fixed radioactivity in the plant to the surface soil at the end of the pasture-growing season. Senescence differs from weathering in that weathering applies to removal of deposits on plant surfaces, while senescence removes radioactivity from internal tissues. In the COMIDA model, senescence is only accounted for pasture grass, and it only starts at the end of the pasture growing season (defined by the end of the livestock grazing season, TEL, Section 2.5.3). NUREG/CR–6613 (Chanin et al., 1998) suggests to derive ZSEN by assuming that most all of the radioactivity in the pasture (e.g., 99.9 percent) returns to the surface soil between the end of the livestock grazing season (TEL) and day 365 of the calendar year. This is consistent with work by Till and Grogan (2008). Figure 2-21 shows the effect of the senescence rate constant is minor on the population dose and the economic cost (at least around baseline inputs). Both the population dose and economic cost decrease with increasing values of the senescence rate constant and attain plateaus at high values of the rate (high values of the senescence rate constant correspond to nearly instant return of radionuclides in pasture to the surface soil after the TEL date).

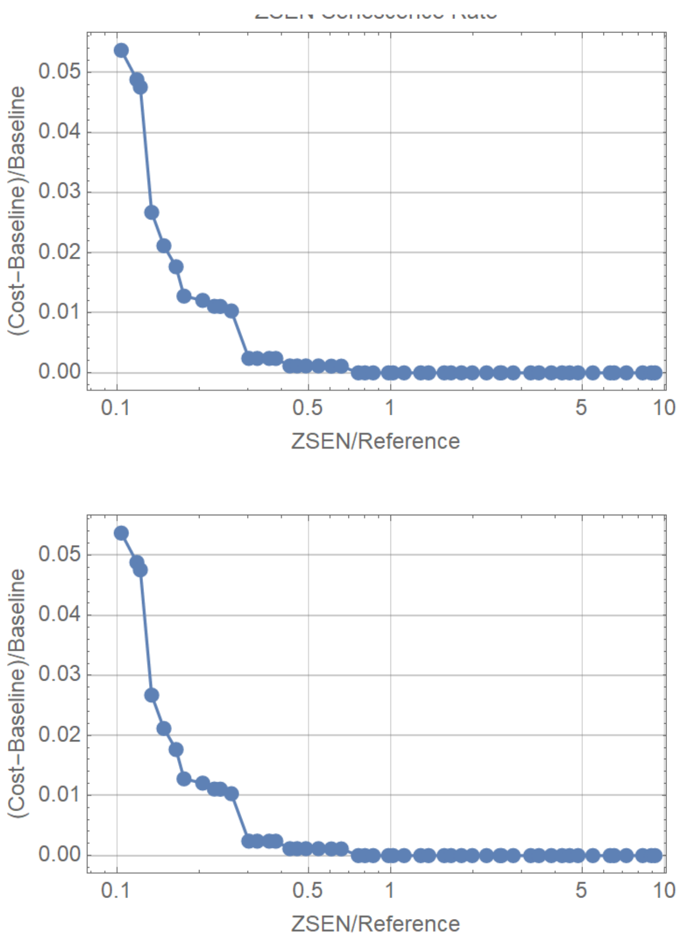


Figure 2-21. Relative change in population dose and economic cost versus normalized senescence rate constant (ZSEN).

Considering the recommendation in NUREG/CR–6613 (Chanin et al., 1998), assuming 99.9 percent of the radioactivity in pasture returns to soil over a span of 60 days, the senescence rate constant is estimated as

$$\mathrm{ZSEN} = -\frac{\ln(1-0.999)}{60\ \mathrm{d}} = 0.12/\mathrm{d} \tag{2-12}$$

2.4.8 Leach Rate Constant (ZKL)

The Leach Rate Constant, ZKL, controls the rate of radionuclide transfer from the labile soil region (root “active” zone) to deep soil. In the COMIDA model, radionuclides transported to deep soil are removed from the soil-plant system and become inconsequential to dose and cost estimates. The transfer mechanism is assumed controlled by the vertical flow of water from irrigation and precipitation, ignoring solubility of mineral phases in soil and filtration of particulates with embedded radioactivity. NUREG/CR–6613 (Chanin et al., 1998) defines ZKL as a function of surface water balance and water-soil partition coefficients (i.e., Kd’s), based on work by Baes and Sharp (1983):

$$ZKL_j = \frac{P + I - E - R}{\theta \, XR \left[1 + \frac{\rho \, Kd_j}{\theta}\right]} \tag{2-13}$$

where

ZKL_j	—	leach rate constant for element j
P	—	annual average precipitation (m d^{-1})
E	—	annual average evapotranspiration (m d^{-1})
I	—	annual average irrigation (m d^{-1})
R	—	annual average surface runoff (m d^{-1})
XR	—	depth of labile (active root zone) soil layer (m) (Section 2.4.1)
θ	—	annual average volumetric water content in the labile soil layer (m^3 m^{-3})
ρ	—	root soil bulk density (kg m^{-3}) (Section 2.4.1)
Kd_j	—	element-specific soil-water distribution coefficient for element j (m^3 kg^{-1})

The COMIDA model accounts for radionuclide sorption to the labile soil, but it disregards chemical reactions with minerals in soil which could constrain the solubility of radionuclide-bearing phases, and explicit limitations on water flows imposed by hydraulic soil conductivity (although such limitations are implicitly accounted for in the annual average surface runoff, if known). The average irrigation in the water balance in the numerator of Eq. (2-13) is crop dependent; however, the COMIDA model accounts for a single value of ZKL for all plant products; thus, ZKL is interpreted as an average over all plant products (five crops, grass, and hay). Radionuclide sorption is soil dependent and element specific. In the COMIDA model, sorption extends retention in the labile soil, which increases the chances for radionuclides to be incorporated in foodstuffs and cause a dose to humans. The COMIDA model requires specification of ZKL for the considered elements.

Information used in Eq. (2-13) such as the annual average volumetric water content in the soil layer, the soil density, the depth of labile (active root zone) soil layer, and the water infiltration may be site-specific. However, the COMIDA model is a simplified model ignoring factors such as solubility constraints, radioactive particle filtration, and difference of irrigation for the various plant products. The COMIDA model also ignores heterogeneity in the soil composition. In addition, Figure 2-22 indicates that the population dose and economic cost are weakly influenced by ZKL, at least around the baseline values. The jumps in the plots in Figure 2-22 are a consequence of the interdiction model. Approximate generic values of ZKL are appropriate for consequence analyses and to approximately explore the dependence of results on retardation in soil, given the small and negligible influence of ZKL to dose and cost estimates.

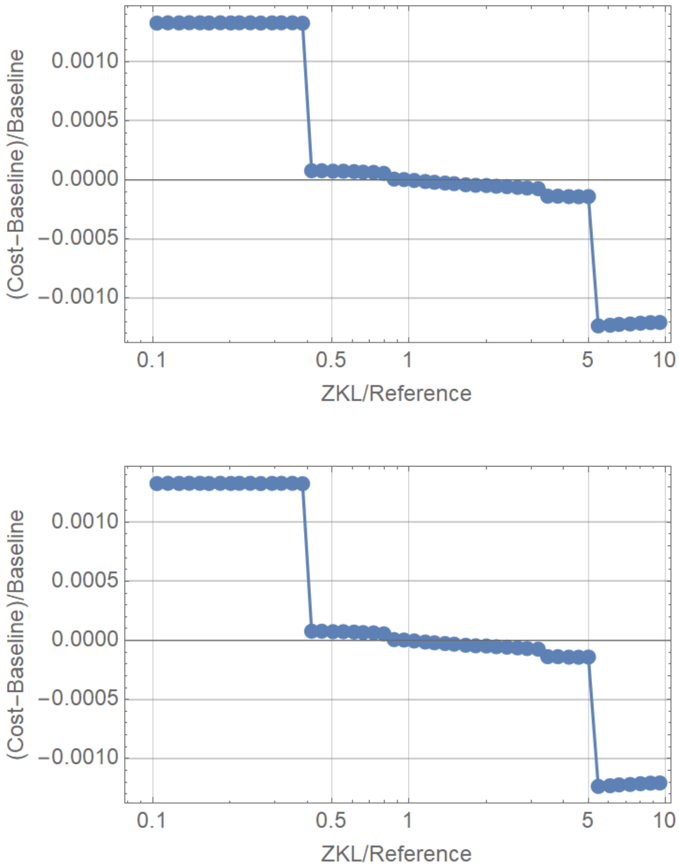


Figure 2-22. Relative change in population dose and economic cost versus the normalized Leach Rate Constant (ZKL)

Values of ZKL in NUREG/CR–6613 (Chanin et al., 1998, Volume 2, Table A-3) were computed from data by Sheppard and Thibault (1990) and Baes et al. (1984) and on generic temperate climate "default" parameters from IAEA (1994). Table 2-8 summarizes information to derive updated values of the leach rate constant, ZKL. Partition coefficients used in the computation of ZKL, and updated ZKL values are listed in Table 2-9. For elements for which information on soil sorption was not available in IAEA (2016) or in the document by Beyeler et al. (1999) (K_d for Ce, La, Ru, and Te), partition coefficients from NUREG/CR–6613 were used (Chanin et al., 1998, Table A-3). Table 2-9 includes associated values of the half-depletion time in years, to provide a notion of the time radionuclides would be depleted in the labile soil compartment by the infiltrating water. The half-depletion time ranges from 1 year (Cs) to approximately 10^4 years (Ru). For elements with long half-depletion times compared to the simulation time, it can be alternatively selected ZKL=0.

Table 2-8. Information to compute leach rate constants in Table 2-9

Information	Comment/Reference
P=annual average precipitation (m d^{-1})	A reference value of 0.84 m/yr was considered, which is the approximate mid-point of weather stations across the United States (Beyeler et al., 1999, Figure 6.24).
E=annual average evapotranspiration (m d^{-1})	An exploratory value equal to 0.42 m/yr was assumed (half of the annual precipitation) (LaPlante et al., 2011).
I=annual average irrigation (m d^{-1})	A reference value of 0.24 m/yr was assumed, based on average irrigation across the United States (Beyeler et al., 1999, Section 6.2.7.4, Table 6.18, and Figures 6.14 and 6.15). Alternatively, Bechtel SAIC (2004a, Table 6.5-2) lists annual irrigation for different plant products for present-day and upper bound glacial transition climates, ranging from 0.4 m/yr to 1.94 m/yr, with an average of 0.95 m/yr. Assuming a lower value for infiltration in the COMIDA2 model overestimates the residence time of radionuclides in the labile soil compartment, increasing the chance for radionuclides to be incorporated in plant tissues.
R=annual average surface runoff (m d^{-1})	An exploratory value of 0 m/yr was assumed.
Annual average volumetric water content in the soil layer (m^3/m^3)	A water content equal to 0.25 was assumed based on information in IAEA (2016, Table 25), reporting water contents ranging from 0.15 to 0.29.
Soil Bulk Density	1,400 kg/m^3, see Section 2.4.1
Depth of labile (active root zone) soil layer	0.1 m, see Section 2.4.1

Table 2-9. Partition coefficients and leach rate constants, ZKL

Element	K_d (L/kg)	ZKL (1/d)	Half depletion time (yr)	Comment/Reference
Am	1,440	9.0×10^{-6}	212	K_d from Beyeler et al. (1999, Table 6.86)
Ba	44.7	2.9×10^{-4}	6.60	K_d from Beyeler et al. (1999, Table 6.86)
Ce	2×10^{4}	6.5×10^{-7}	2,941	K_d from NUREG/CR–6613, Volume 2 (Chanin et al., 1998, Volume 2, Table A-2, organic soil) and Sheppard and Thibault (1990)
Cm	9,300	1.4×10^{-6}	1,368	K_d from IAEA (2010, Table 14)
Cs	447	2.9×10^{-5}	66	K_d from Beyeler et al. (1999, Table 6.86)
I	7	1.8×10^{-3}	1	K_d from IAEA (2010, Table 12)
La	650	2.0×10^{-5}	96	K_d from NUREG/CR–6613, Volume 2 (Chanin et al., 1998, Volume 2, Table A-2), and Baes et al. (1984)
Pu	955	1.4×10^{-5}	140	K_d from Beyeler et al. (1999, Table 6.86)
Ru	6.6×10^{4}	2.0×10^{-7}	9,704	K_d from NUREG/CR–6613, Volume 2 (Chanin et al., 1998, Volume 2, Table A-2, organic soil) and Sheppard and Thibault (1990)
Sr	31.6	4.1×10^{-4}	4.70	K_d from Beyeler et al. (1999, Table 6.86)
Te	1.9×10^{3}	6.8×10^{-6}	279	K_d from NUREG/CR–6613, Volume 2 (Chanin et al., 1998, Volume 2, Table A-2, organic soil) and Sheppard and Thibault (1990)

2.4.9 Adsorption Rate Constant (ZKAD) and Desorption Rate Constant (ZKDE)

COMIDA implemented a special model to simulate long-term fixation of cesium isotopes to soil. Elements may be absorbed to clay particles in soil and become less available for root uptake as time elapses. The COMIDA model includes a compartment named “fixed soil” (Figure 2-1) to simulate long-term fixation of radionuclides to soil particulates. For most elements, the fixation is relatively rapid, and fixation is implicitly accounted for with the selection of plant-to-soil equilibrium concentration ratios (Abbott and Rood, 1993, 1994). However, for cesium the soil-fixation process is gradual. Abbott and Rood (1993, 1994) cited studies by Squire and Middleton (1966) concluding that Cs-137 root uptake decreased by approximately 90 percent in soils with clay over a period of five years (in other words, the effective Cs-137 plant-to-soil equilibrium concentration ratio would apparently decrease as a function of time, with a decrease of 90 percent over five years). Abbott and Rood (1993, 1994) introduced the “fixed soil” compartment in the COMIDA model to account for reduced cesium isotope root uptake as time elapses. It is noted that the COMIDA2 model and its WinMACCS interface allows to input sorption and desorption coefficients for all tracked radionuclides (not only for cesium isotopes); however, Abbott and Rood (1993, 1994) recommended specific input values based on experimental work on Cs-137 uptake in pastures by Squire and Middleton (1966). The WinMACCS interface includes explanatory notes indicating that sorption (ZKAD) and desorption (ZKDE) rate constants should only be specified for cesium isotopes. The fixed soil compartment effectively extends the residence time of cesium isotopes in the root soil compartment (see Table 2-9 for the cesium half depletion time due to leaching; this leaching time is extended due to the action of the fixed soil compartment).

In the COMIDA model, the labile soil compartment exchanges cesium mass with the fixed soil compartment through a first order rate (i.e., the rate of mass transfer from labile soil to fixed soil is proportional to the cesium mass in the labile soil compartment; the proportionality constant is the adsorption rate, ZKAD, with units of 1/time; the reverse mass exchange proportionality constant is the desorption rate, ZKDE). As an example of the derivation of the ZKAD and ZKDE rate constants, assuming all of the cesium mass is initially in the labile soil compartment, and ignoring radioactive decay and any other mass transfer with any other compartment, the radionuclide mass in the labile soil and fixed soil compartments as a function of time is given by

$$\frac{m_L(t)}{m_o} = \frac{k_d + k_a e^{-(k_a+k_d)\,t}}{k_a + k_d} \tag{2-14}$$

$$\frac{m_F(t)}{m_o} = \frac{k_a}{k_a + k_d}\left(1 - e^{-(k_a+k_d)\,t}\right) \tag{2-15}$$

where m_o is the total mass at time 0 in the labile soil compartment (the initial mass in the fixed soil compartment is 0), $m_L(t)$ and $m_F(t)$ are radionuclide masses in the labile soil compartment at time t, and k_a=ZKAD and k_d=ZKDE are the absorption and desorption rate constants. The rate constants that satisfy $m_L(t$=5 years)=0.1 m_o and $m_F(t$=5 years)=0.9 m_o equal ZKAD=2.3×10^{-3} 1/day and ZKDE=2.3×10^{-4} 1/day. These sorption and desorption rates compare well to the values Abbott and Rood (1993, 1994) proposed, equal to ZKAD=1.9×10^{-3} 1/day and ZKDE=2.1×10^{-4} 1/day. Figure 2-23 displays the relative mass in the labile and fixed soil compartments (ignoring radioactive decay) as a function of time for the case ZKAD=2.3×10^{-3} 1/day and ZKDE=2.3×10^{-4} 1/day.

The plots in Figure 2-24 indicate minimal variation in population dose and negligible change in the economic cost with cesium adsorption and desorption rates. There are competing effects

associated with sorption to fixed soil. Increasing ZKAD increases the time cesium is retained in the system, potentially spreading detrimental effects in time; on the other hand, the retained cesium isotopes in the fixed-soil compartment is inconsequential to dose and cost. Figure 2-24 shows that the population dose and cost monotonically decrease with increasing sorption rate constant ZKAD. The jumps in the economic cost curve arise from the interdiction model and the use of critical concentrations to apply different land condemnation and decontamination actions.

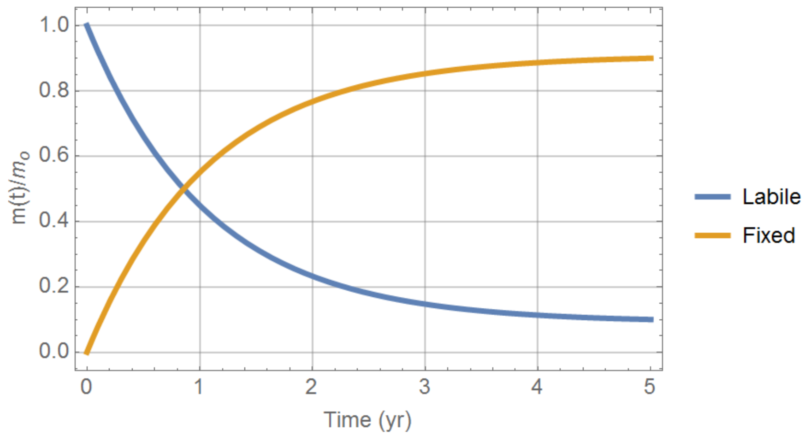


Figure 2-23. Relative mass in the labile soil and fixed soil compartments as a function of time assuming ZKAD=2.3×10^{-3} 1/day and ZKDE=2.3×10^{-4} 1/day, and ignoring decay and mass transfer with other compartments.

Values equal to ZKAD=2.3×10^{-3} 1/day and ZKDE=2.3×10^{-4} 1/day are proposed as updated input values for cesium isotopes, based on work by Squire and Middleton (1966), and information in Figure 2-24 indicating minimal dependence of the total population dose on these parameters, and negligible change in the economic cost with variation in ZKAD and ZKDE. For other elements than cesium, ZKAD = ZKDE = 0.

It is again highlighted that the parameter pair {ZKAD, ZKDE} is an adjustment in the COMIDA model developed by Abbott and Rood (1993, 1994) to account for decreased availability with time of cesium isotopes in soil to be incorporated in plants. It was interpreted that such reduction is associated with gradual sorption of cesium to clay particles. The pair {ZKAD, ZKDE} must be designed to match experimental observations of plant-to-soil concentration ratios as a function of time; and the reader is cautioned against blind use of information from sorption-desorption experiments to define independent values for ZKAD and ZKDE for cesium isotopes or any other radionuclide.

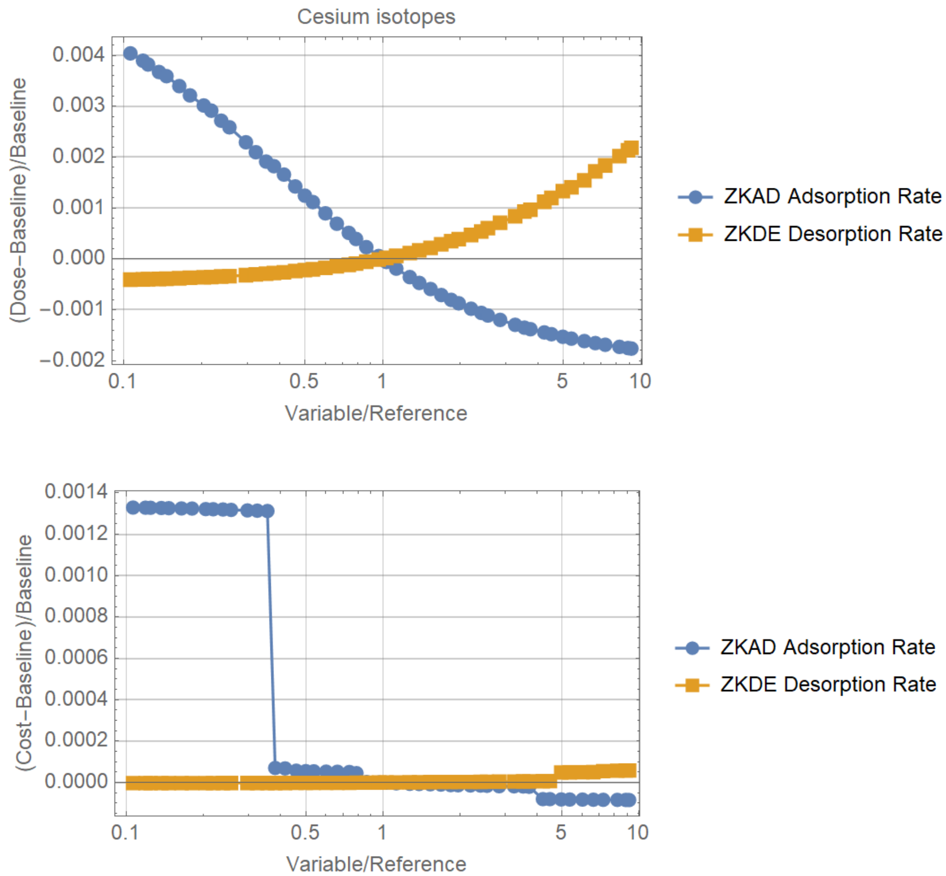


Figure 2-24. Relative change in population dose and economic cost versus normalized cesium adsorption (ZKAD) and desorption rate (ZKDE) constants

2.4.10 Root Uptake and Concentration Ratio (CR)

The concentration ratio (CR) is a group of element-specific parameters used to calculate the rate of root uptake in seven different types of crops consumed by farm animals and humans. The term concentration ratio is more commonly referred to as the soil-to-plant transfer factor in the literature although several different terms for this parameter have been used. The concentration ratio is a ratio of the activity concentration of radionuclides in the plant (Bq g^{-1} dry matter) to the concentration in soil (Bq g^{-1} dry matter). The CR in the COMIDA model was formulated using a method developed for the PATHWAY model (Whicker and Kirchner, 1987).

In the COMIDA model, the rate of root uptake (for each of the seven crop products and each radionuclide) is computed as (Abbott and Rood, 1993, 1994)

$$R_{up} = \frac{Q_L}{x_L \, \rho_L} B'(t) \, CR \qquad (2\text{-}16)$$

where

R_{up} — rate of root uptake for the specific plant product and radionuclide (Bq/m^2-day)

Q_L — radioactivity in the labile soil compartment for the specific crop type and radionuclide (Bq/m^2)

x_L	—	thickness of the labile soil (root zone) compartment (m) (Section 2.4.1)
ρ_L	—	density of the labile soil compartment (kg/m^3) (Section 2.4.1)
$B'(t)$	—	derivative of the plant biomass computed with Eq. (2-1) and BMAX for the specific plant product (dry kg/m^2-day)
CR	—	concentration ratio or soil-to-plant transfer factor (Bq/kg dry plant per Bq/kg dry soil)

To gain understanding of the root uptake model a simple example is examined. Considering mass exchange only between the labile soil compartment and the plant internals compartment (i.e., ignoring other compartments and radioactive decay), the mass balance equations for Q_L and Q_V (vegetable internals) are

$$\frac{dQ_L}{dt} = -R_{up} = -\frac{Q_L}{x_L\,\rho_L} B'(t)\,CR \tag{2-17}$$

and

$$\frac{dQ_V}{dt} = +R_{up} = \frac{Q_L}{x_L\,\rho_L} B'(t)\,CR \tag{2-18}$$

Assuming $Q_L(t=0)=Q_o$ and $Q_V(t=0)=0$ as initial conditions, the solution to the simplified system of equations is

$$Q_L(t) = Q_o \exp\left\{-\frac{CR}{x_L\,\rho_L}[B(t) - \mathrm{BI}]\right\} \tag{2-19}$$

and

$$Q_V(t) = Q_o\left(1 - \exp\left\{-\frac{CR}{x_L\,\rho_L}[B(t) - \mathrm{BI}]\right\}\right) \tag{2-20}$$

Experiments to determine the concentration ratio, CR, are performed in systems where the soil is an infinite source, with radionuclide inventory not depleted by plant uptake. Such limiting condition is equivalent to assuming that the argument of the exponential term is a small number (so that $Q_L \approx Q_o$). By applying a Taylor's series expansion to Eq. (2-20) in the limit when the argument of the exponential function is small, Eq. (2-20) becomes

$$Q_V(t) \approx Q_o\,\frac{CR}{x_L\,\rho_L}[B(t) - \mathrm{BI}] \tag{2-21}$$

Therefore, the concentration ratio is defined as

$$CR = \frac{Q_V(t)}{B(t) - \mathrm{BI}} \bigg/ \frac{Q_o}{x_L\,\rho_L} \tag{2-22}$$

Equation (2-22) is consistent with the experimental determination of the soil-to-plant factor, as the ratio of radioactivity in the plant per unit of dry plant mass to the radioactivity in the soil per unit of dry soil mass. Therefore, the definition of the root uptake rate in Eq. (2-16) is consistent with the standard definition of the concentration ratio.

Figure 2-25 displays the relative change in population dose and economic cost versus normalized concentration ratios. As explained in Section 2.1, radionuclide-specific concentration

ratios were varied simultaneously using the rank-correlation MACCS function. The horizontal axis in Figure 2-25 is the normalized concentration ratio averaged over all radionuclides. The change in population dose and economic cost is relatively small. The individual dose increases with increasing values of CR, and this explains the increasing trends in the population dose and economic cost in Figure 2-25.

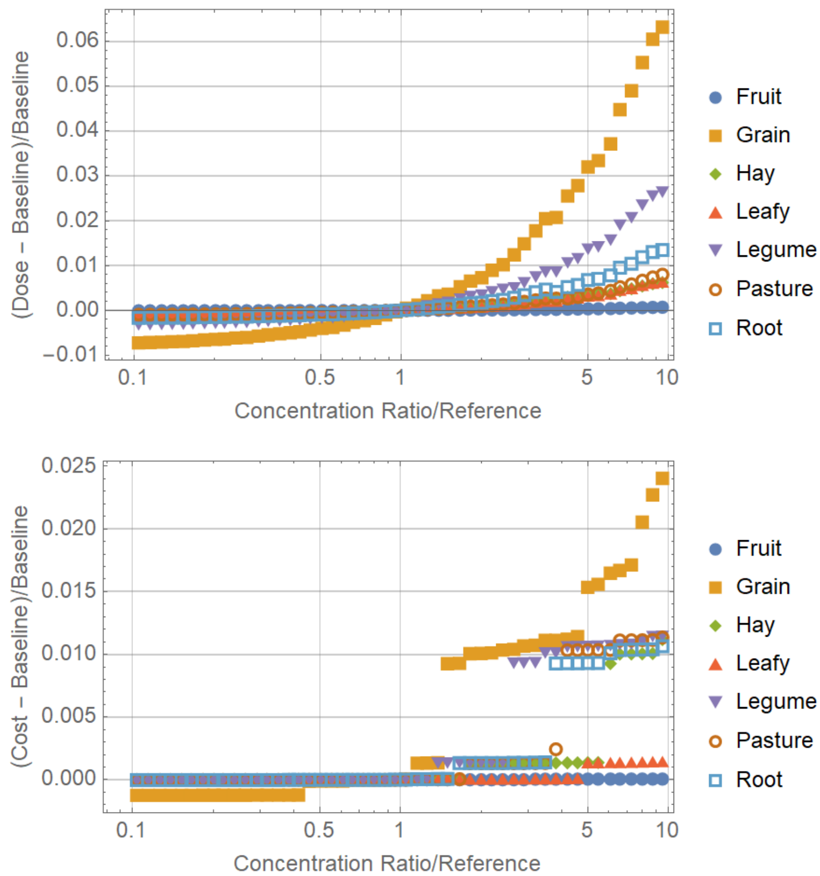


Figure 2-25. Relative change in population dose and economic cost versus the normalized concentration ratio (CR)

In the section titled "Process Governing Radionuclide Transfer to Plants" in IAEA (2009), references are provided addressing CR per radionuclide for different plant products. A databank maintained by the International Union of Radioecology contains information on soil-to-plant transfer factors with other extensive information (IUR, 1992). Updated concentration ratios are compiled in Table 2-10, based on in the most recent compilation available from the IAEA (2010). Table 2-10 includes assumed values for specific plant products, based on alternative maximum values for the same element (data located along a row in Table 2-10), and highlighted in bold font.

Table 2-10. Updated concentration ratios, CR (soil to plant transfer factors)

Element	Grains*	Leafy Vegetables*	Roots*	Fruit†	Legume*	Pasture*	Hay*	Comment
Am	2.2E-05	2.7E-04	6.7E-04	3.1E-05	3.8E-04	1.5E-03	3.3E-02	
Ba	1.0E-03	5.0E-03	5.0E-03	1.5E-02	0.91	**2.0**	2.0	CR of pasture assumed equal to hay
Ce	3.1E-03	6.0E-03	6.0E-03	5.3E-04	1.3E-02	0.37	2.0E-02	
Cm	2.3E-05	1.4E-03	8.5E-04	5.3E-04	7.5E-04	1.0E-03	**1.0E-03**	CR of hay assumed equal to pasture
Cs	2.9E-02	6.0E-02	4.2E-02	5.8E-03	4.0E-02	2.5E-01	6.3E-02	
I	2.0E-02	3.4E-03	2.0E-02	6.3E-03	**2.0E-02**	**2.0E-02**	**2.0E-02**	CR of legume, pasture, and hay assumed equal to grains
La	2.0E-05	5.7E-03	1.6E-03	**2.0E-02**	4.2E-04	2.0E-02	1.8E-05	CR of fruit assumed equal to pasture
Pu	9.5E-06	8.3E-05	3.9E-04	1.4E-04	6.3E-05	5.5E-04	1.6E-04	
Ru	3.0E-03	9.0E-02	1.0E-02	1.3E-03	1.5E-02	**9.0E-02**	**9.0E-02**	CR of pasture and hay assumed equal to leafy vegetables)
Sr	0.11	0.76	0.72	1.7E-02	1.4	1.3	0.91	
Te	0.10	0.30	0.30	**1.0**	**1.0**	1.0	**1.0**	CR of fruit, legumes, and hay assumed equal to pasture

*IAEA, 2010 Table 17
†IAEA, 2010 Table 19

2.4.11 Sensitivity Plots of Parameters Associated with Soil-Plant Transfer Processes

Figure 2-26 is provided to facilitate comparing the variability of the population dose and economic cost with respect to input parameters controlling soil-plant rates of transfer [the concentration ratio (CR) and the foliar absorption rate constant (ZKAB) are not included in Figure 2-26]. The percolation rate (ZKP) and the resuspension rate (ZKR) are two important inputs affecting the population dose. Both are related to mobilization of contaminants away from the surface soil compartment (towards the root soil compartment in the case of ZKP, and towards plant surfaces in the case of ZKR). The weathering rate (ZKW) has an important influence on the population dose due to its relationship of removal of radioactivity from plant surfaces, which otherwise can translocate and assimilate in plant tissues. The relevance of ZKW should be cautiously interpreted, because the relationship to the foliar absorption rate constant (ZKAB) was ignored in the sensitivity analysis.

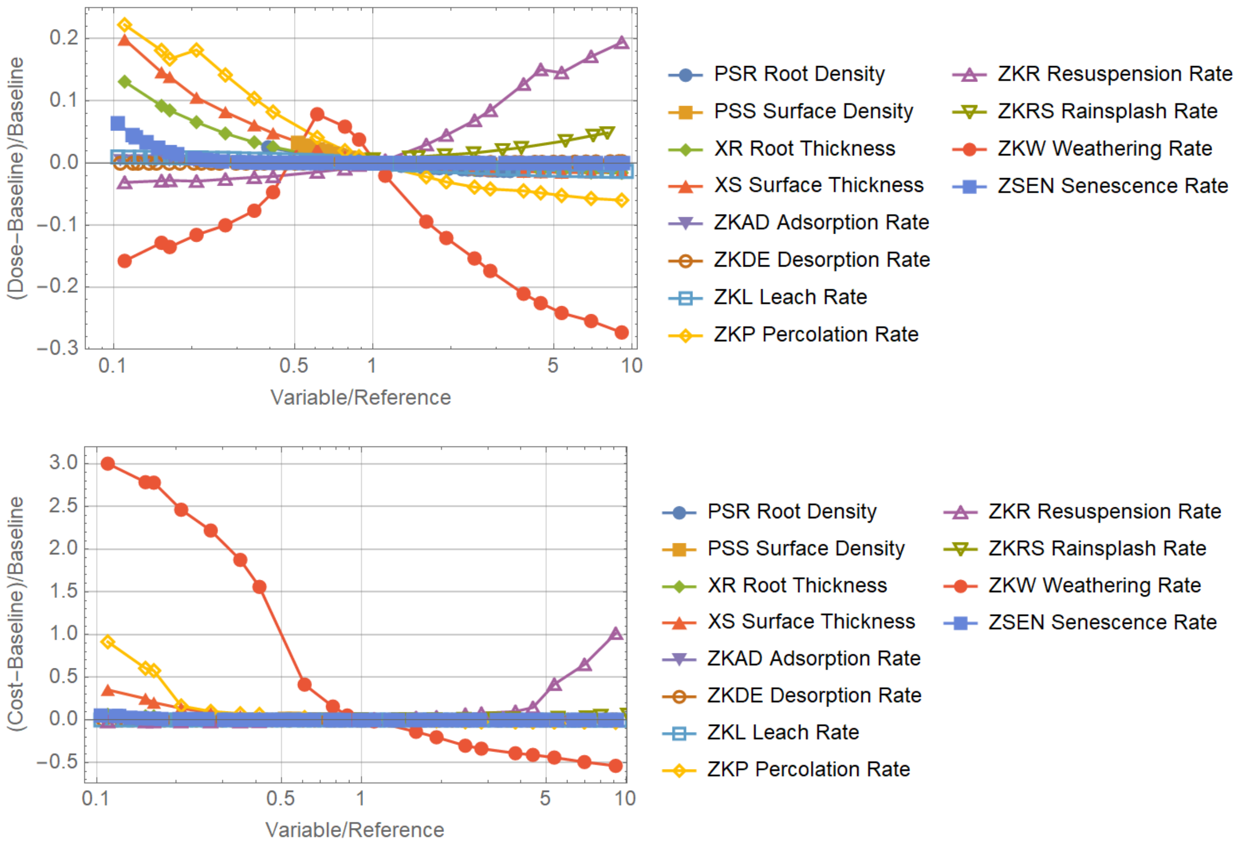


Figure 2-26. Relative change in population dose and economic cost versus relative inputs related to soil-plant transfer processes [the concentration ratio (CR) and the foliar absorption rate constant (ZKAB) are not included in the plot]

2.5 Agricultural Dates

The COMIDA model includes a series of time inputs to define discrete agricultural events such as tillage, beginning and end of the crop growing season, and beginning and end of the grazing season. The original COMIDA model outputs the concentration of crop products (Bq/kg) at the time of harvest, and concentrations in animal products (Bq-d/kg) integrated over the accident year (accounting for a delay time for human consumption, and radionuclide decay and ingrowth). The COMIDA2 model extended computations of the original COMIDA model to account for delay in the human consumption time of crops after harvest, and consumption of animal products throughout the accident year, to compute individual doses.

For the one-parameter-at-a-time sensitivity runs, the time parameters were varied within a range spanning 40 or 60 days. For the computation of slopes as sensitivity indices, the input parameters were linearly transformed to span from a minimum of −1 to a maximum of 1, with 0 representing the baseline value, and then a linear regression was computed. However, for the sake of clarity, the untransformed variables are presented in the scatter plots in this Section 2.5 and compared to the nine accident dates considered in the computations. The sequence of agricultural time parameters in the Sample Problem LNT input file is shown in Figure 2-27, including nine assumed accident dates.

The dates in Figure 2-27 correspond to approximately general farming practices in North America, and are reasonable selections, recognizing the approximated nature of the COMIDA2 model. As an example of one approximation, the COMIDA2 model requires a single harvest date for all crops (TEC), when in reality some products, such as leafy vegetables and roots, are harvested at multiple times. In general, the population dose end economic cost estimates (over a multi-year simulation period) are not highly sensitive to changes in the agricultural input dates but respond to whether a fallout event is postulated to occur near the beginning or end of a period. The sensitivity results are presented in the next sections.

The COMIDA2 model require specification of up to nine postulated accident dates. The accident dates in the Sample Problem LNT input file are well spread throughout the year and were selected to avoid precise overlap with other agricultural practice dates. These postulated accident times span a reasonable range to examine consequences of accidents before, during, and after agricultural production periods.

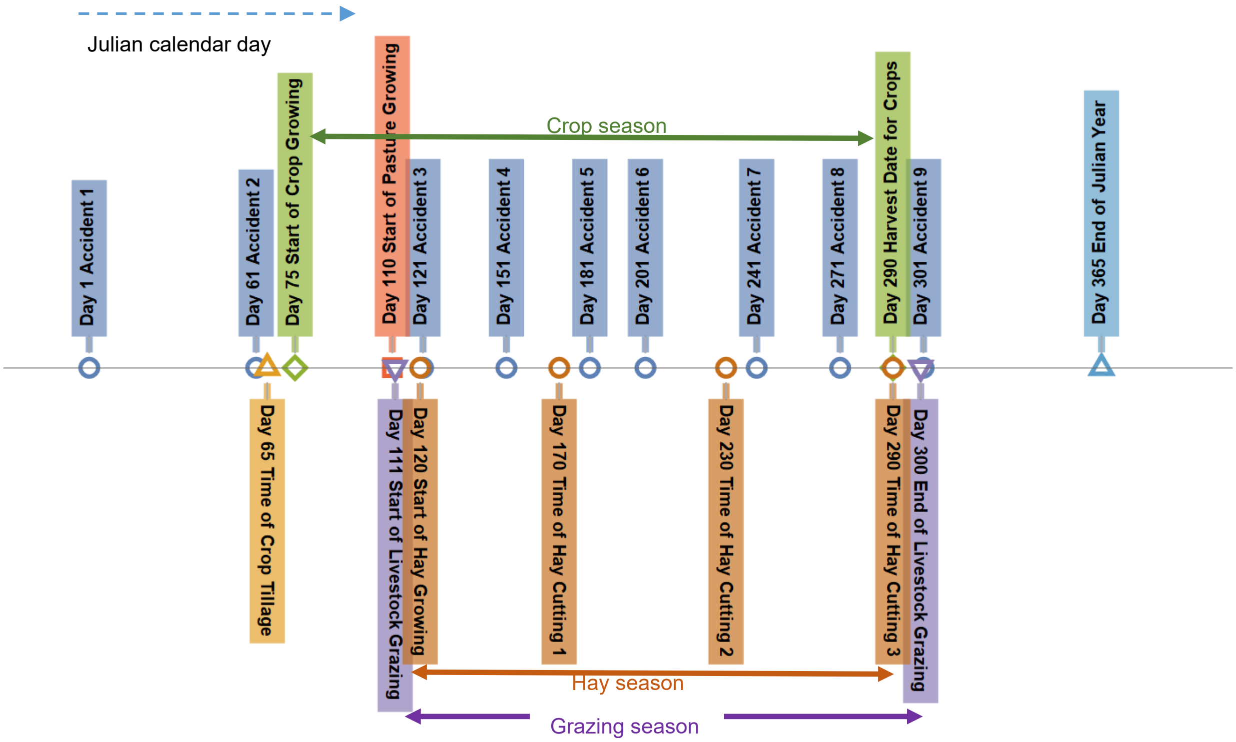


Figure 2-27. Sequence of agricultural times and accident dates in the Sample Problem LNT input file (the horizontal axis represents the Julian day in the calendar year)

2.5.1 Time of Crop Tillage (TT)

Tillage refers to the preparation of land for growing crops by digging, stirring, and overturning soil. In the COMIDA model, at the tillage time (TT) the contamination is assumed uniformly re-distributed between the surface soil compartment and the labile soil compartment. After the time of tillage, the total contamination in the surface soil and labile soil compartments is proportioned according to the mass per unit of volume defined by the product (soil density) × (soil thickness). The WinMACCCS interface only takes one input date TT for all plant products; thus, TT is interpreted to be an average over all crops, pasture, and hay. Note that soil compartments for the seven plant products in the COMIDA model are independent from each other; thus, tilling does not mix soil of different plant products. Also, the fixed soil compartment is assumed unaffected by tilling (in other words, cesium immobilized in the fixed soil compartment remains immobilized after tilling).

For the sensitivity analysis, the parameter TT was varied by ±30 days around the baseline value of 65 days. The population dose and the total cost are almost independent on the TT parameter (Figure 2-28). Within the 60-day time domain of the plot, there is only one postulated event at 61 days (accident number 2, date indicated with a red dot). The total dose and the economic cost drop to the baseline value if tillage occurs after the accident. The COMIDA model is not sensitive to small variations in the time of crop tillage. The sudden change in the COMIDA outputs is related to whether tillage occurs before or after a fallout event. Tillage after the event redistributes the surface contamination in a larger volume of labile soil and causes a minor decrease in consequences (population dose and economic cost).

A value of TT=65 days is appropriate for general analyses. As previously stated, the COMIDA model outputs are practically independent of the TT date, except for variations depending on the accident date. For model consistency it is important to maintain the sequence TT < start of crop growing season and TT < start of pasture growing season. However, the COMIDA model can implement redistribution of contaminant by tillage at any time during the crop or pasture growing season; it is up to the user to ensure consistency of the input agricultural dates.

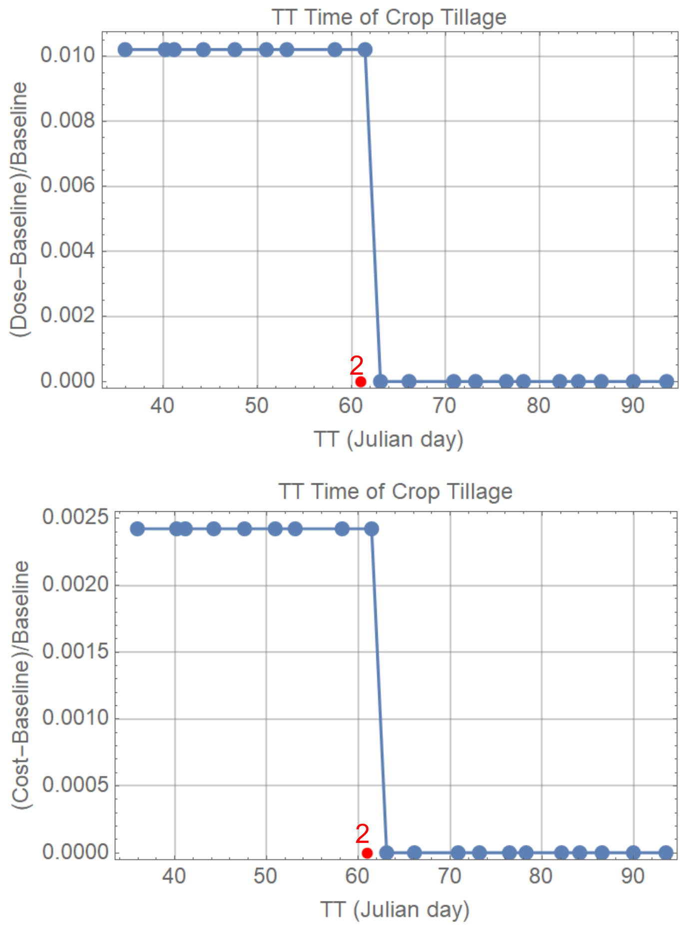


Figure 2-28. Relative change in population dose and economic cost versus the time of tillage (TT). The red dot is the relevant accident date (accident number 2; eight other accident dates are outside the time domain of the plots)

2.5.2 Crop Growing Season: Start of the Crop Growing Season (TSC) and Harvest Day for Crops (TEC)

The crop growing season is defined by the start date (TSC) and the harvest date (TEC). The COMIDA model assumes the same dates for all five crops. Figure 2-29 is provided to facilitate interpretation of results with respect to variation of TSC and TEC. Shortening the growing period for crops can be accomplished by delaying TSC or harvesting sooner. Limited shortening of the growing period does not have a significant effect for crops of rapid growth such as leafy vegetables and roots. Shortening of the growing period could reduce radioactivity concentrations on slowly growing crops such as fruits and grains, depending on when the fallout accident happens. By contrast, increasing the growing period (by decreasing TSC or increasing TEC) could increase the radioactivity concentration of slowly growing crops.

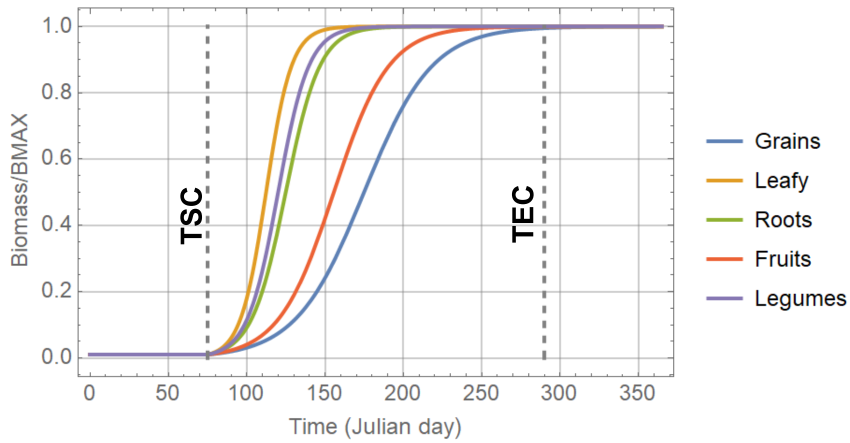


Figure 2-29. Biomass [Eq. (2-1)] versus time for five crop products, start of growing season (TSC), and harvest day (TEC).

Figure 2-30 shows the variation in total population dose and economic cost versus the beginning (TSC) and end (TEC) of the crop growing season. The red dots represent postulated event dates in the simulations. The results confirm the assessment in the previous paragraph that food concentrations decrease (and the population dose) when the growing period is shortened (either by increasing TSC or decreasing TEC), and the opposite occurs when the growing period is extended (either by decreasing TSC or increasing TEC). However, simple duration effects confounded with other effects related to when the accident occurs in the growing season, as well as interdiction model effects. For example Accident 2 (labeled with 2 in the left-hand side plots in Figure 2-30) occurs before the growing season in the baseline case, but in the sensitivity runs, some instances of TSC place the Accident 2 after the start of the growing season, causing enhanced interdiction effects. The extent of interdiction actions decrease if the Accident 2 occurs before the start of the growing season. The interdiction actions and the decrease in the individual dose with increasing values of TSC cause the local maximum in the population dose versus TCS (top left plot in Figure 2-30). Similarly, Accident 9 occurs after the harvest in the baseline run, but in the sensitivity run some instances of TEC place the Accident 9 before the harvest date, causing enhanced interdiction actions when TEC > Accident 9 date. The increasing trend in the population dose after Accident 9 (top right plot in Figure 2-30) correlates with the decreasing economic cost after Accident 9 (lower right plot in Figure 2-30). Most of the radioactivity in the crop products for cases when the accident is close to the harvest time arises from surface contamination of the plants and translocation. In summary, under relatively constant interdiction actions, the individual dose increases with increasing values of TSC and decreases with increasing values of TEC, which cause similar trends in the population dose. However, sharp changes in consequences occur when the beginning or end of the crop growing season are close to postulated event dates. If harvest occurs shortly after an accident, crops include may include substantial surface contamination, which would cause substantial interdiction actions with the associated economic costs, and control of the population dose.

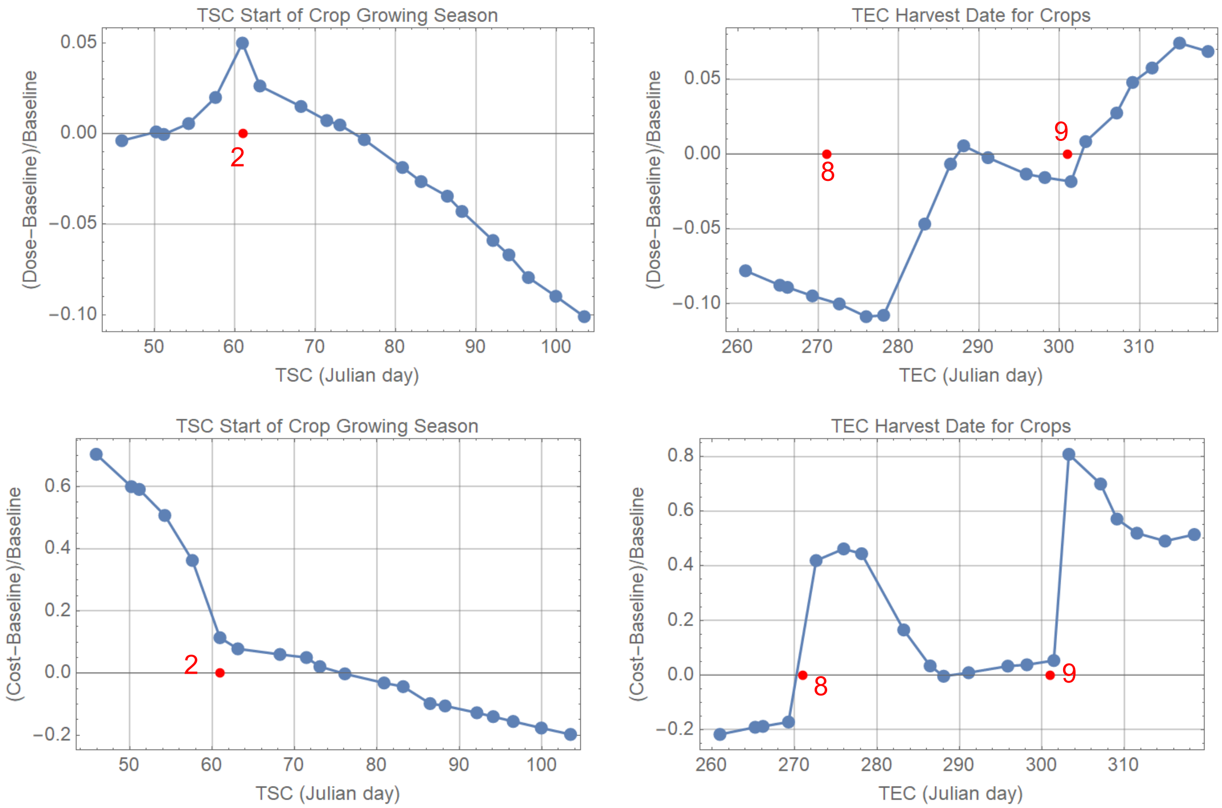


Figure 2-30. Relative change in population dose and economic cost versus the start (TSC) and end (TEC) of the crop growing season. The red dots are postulated accident dates (accidents 2, 8, and 9).

2.5.3 Grazing Season: Start of Pasture Growing Season (TSP), Start of Livestock Grazing Season (TSL), and End of Livestock Grazing Season (TEL)

Figure 2-31 displays the pasture growth, the start of the pasture growing season (TSP), the start of the livestock grazing season (TSL), and the end of the livestock grazing season (TEL), to facilitate explaining the sensitivity results, and to exhibit some approximations of the COMIDA model. The times TSP and TSL are separated by one day in the baseline case, and they visually overlap in the scale of the plot in Figure 2-31. After approximately Julian day 150, the biomass curve reaches a plateau, and in the COMIDA model the grass root uptake of contaminants practically stops. Thus, accidents after day 150 would not cause contamination of grass by root uptake (but only by surface translocation) during the first year after the accident. The COMIDA model disregards the continuous growth of the grass after cattle grazing; instead, the COMIDA model assumes grass actively grows only during a short period after TSP. Therefore, the COMIDA model may underestimate grass root uptake of radioactivity. Section 2.3.3 presents an alternative derivation of the pasture growth rate, ZKG, to balance this underestimation (see Figure 2-12 and explanatory text).

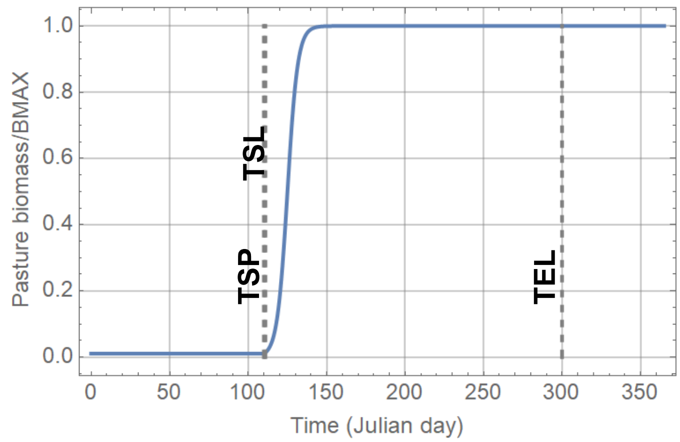


Figure 2-31. Pasture biomass versus time, start of pasture growing season (TSP), start of livestock grazing season (TSL), and end of livestock grazing season (TEL).

Figure 2-32 shows the sensitivity of the outputs to the start and end of the livestock grazing season, and to the start of the pasture growing season. Both TSP and TSL were simultaneously varied (TSL = TSP + 2 days) to avoid instances where cattle and cows would start grazing before pasture would start growing. Figure 2-32 also includes the milk disposal area versus TSP and TEL to rationalize trends. At TSP < Accident 3 date, the milk disposal area increases with increasing values of TSP. If TSP is after Accident 3, the milk disposal area becomes a decreasing function of TSP. This decreasing trend in the milk disposal area at TSP > Accident 3 date, correlates with the decreasing economic cost and the increasing population dose.

With respect to variation of TEL, the plots on the right-hand-side of Figure 2-32 all reflect increasing trends with increasing TEL. The population dose curve is highly correlated to the milk disposal area. The increasing trend suggest that the individual dose increases with increasing TEL. The Accident 9 occurs near TEL; however, the effect of Accident 9 on the consequence curves is minor (if an event occurs near the end of the grazing season, its effect must be minor during the year of the accident). The range of variation of the population dose and the economic cost with respect to variation in TEL is minor, at least around the baseline case.

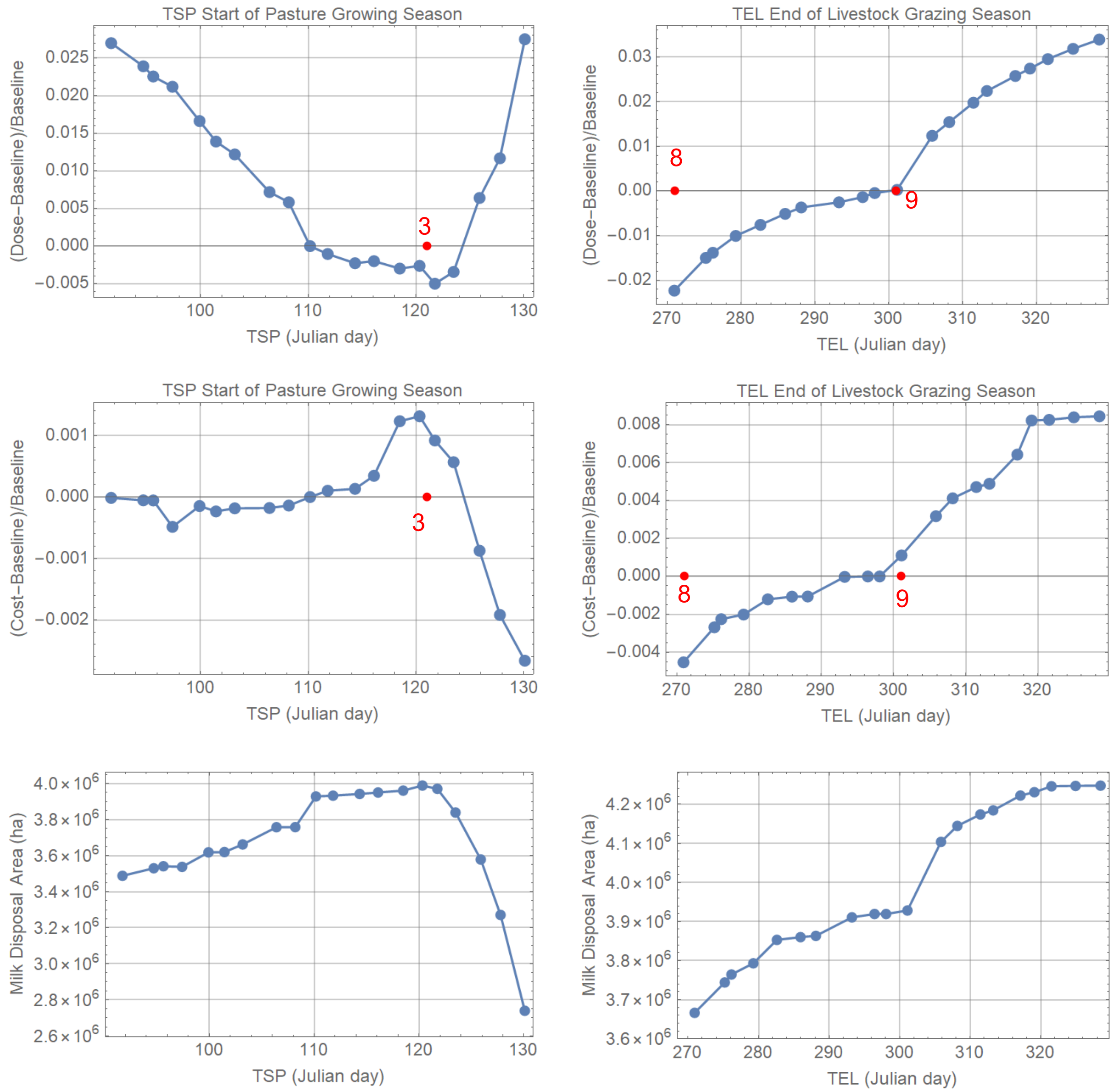


Figure 2-32. Relative change in population dose and economic cost versus the start (TSP) of the pasture growing season and end (TEL) of the livestock grazing season. The red dots are postulated accident dates. The run with TSP variation simultaneously varied the start of the livestock grazing season (TSL) (TSL = TEL + 2 days).

2.5.4 Hay Growing Season: Start of Hay Growing Season (TSH) and Hay Cutting Times (TCUT)

Figure 2-33 compares the plot of the hay biomass to the start of the hay growing season (TSH) and three hay cutting dates. In the baseline inputs, it is assumed that TSH and the hay cut dates are separated by 60 days. The COMIDA model computes the radioactivity concentration in hay at the three harvest dates, and tracks the harvested hay in a separate storage compartment (different than the soil and plant compartments depicted in Figure 2-1) for the computation of decay and ingrowth. The COMIDA model computes the radioactivity inventory of the three harvests, and propagates the inventory (accounting for decay an ingrowth) to the last cutting date, TCUT 3. A simple arithmetic average of the three harvests is used as input to compute radioactivity intake by animals throughout the feeding season. The COMIDA model assumes that a constant amount of harvest is consumed every calendar year, which is perfectly balanced with the production of hay. Animal feeding before TCUT 1 plus a constant hay feed delay time (THHAY, Section 2.6.2) employs hay from the previous calendar year; feeding after TCUT 1 + THAY employs hay harvested during the current calendar year. The COMIDA documentation highlights the use of average hay inventories at time TCUT 3 [e.g., Abbott and Rood, 1993, Eq. (21)] as input to the computation of radioactivity concentration in animal products, but it is not clear how radionuclide decay and ingrowth are handled, especially to feed animals between TCUT 1 + THAY and TCUT 3 + THAY. As an approximation, the COMIDA model may not apply any further decay and ingrowth corrections for hay consumed during the current calendar year (other than corrections accounting for a constant delay time, THAY). Further decay and ingrowth corrections may apply only to stored hay consumed in the following calendar year. The COMIDA model is an approximated it its treatment of stored feed consumed throughout the year.

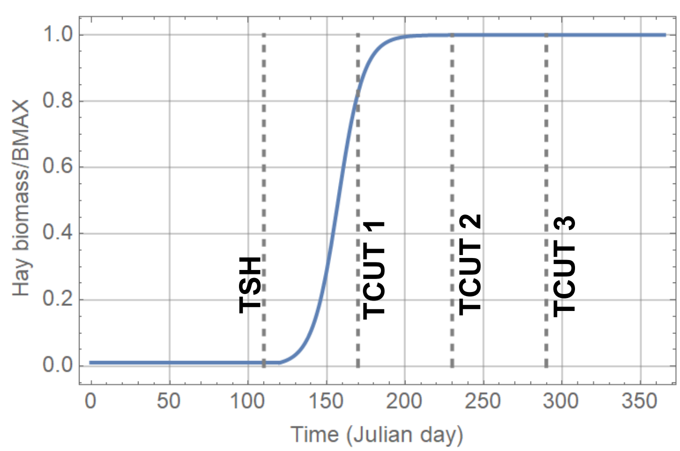


Figure 2-33. Hay biomass versus time, start of hay growing season (TSH), and hay cutting dates (TCUT 1, 2, and 3).

With respect to sensitivity of results to variation in TSH, delaying the start of the hay growing season, is equivalent to displacing the sigmoidal curve in Figure 2-33 to the right, which decreases the radioactivity concentrations in hay at the hay cut dates, lowering individual doses. The opposite occurs if TSH is moved to earlier times in the calendar year, the hay concentrations slightly increase, increasing individual doses. Figure 2-34 shows the sensitivity of the outputs to the start of the hay growing season, which confirm the predicted trends: the population dose and economic cost are decreasing functions of TSH. In this case, having the start of the hay growing season close to an accident (Accident 3, red dot in Figure 2-34) does

not cause a jump in the consequences due to the use of average concentrations over three hay cutting dates.

Figure 2-35 shows the variation of the outputs versus the dates of hay cuttings. The hay cutting dates TCUT 1, TCUT 2, and TCUT 3 were simultaneously varied such that TCUT 2 = TCUT 1 + 60 days, and TCUT 3 = TCUT 1 + 120 days. The population dose and total economic cost versus TCUT 1, TCUT 2, and TCUT 3 are shown in Figure 2-35, to facilitate comparison of sharp changes with accident dates. Sudden changes in the dose and cost occur near postulated accident dates (red dots for Accidents 4, 5, 7, 8, and 9). The sharp change at date 181 in the top plots is an artefact of coincidences in the run inputs with accident dates. Runs with TCUT 1 near day 181, TCUT 2 near day 241, and TCUT 3 near day 301 simultaneously coincide with the postulated Accidents 5, 7, and 9. Those three coincidences cause the sharp jump in the right-hand side of the plots in Figure 2-35. Note however, that changes are relatively minor in both the population dose and economic cost. In between accident dates, the variation of the population dose and total economic cost with changes of TCUT is minor. The main changes are associated with when the accident occurs within the hay growing season in relationship to hay cutting dates.

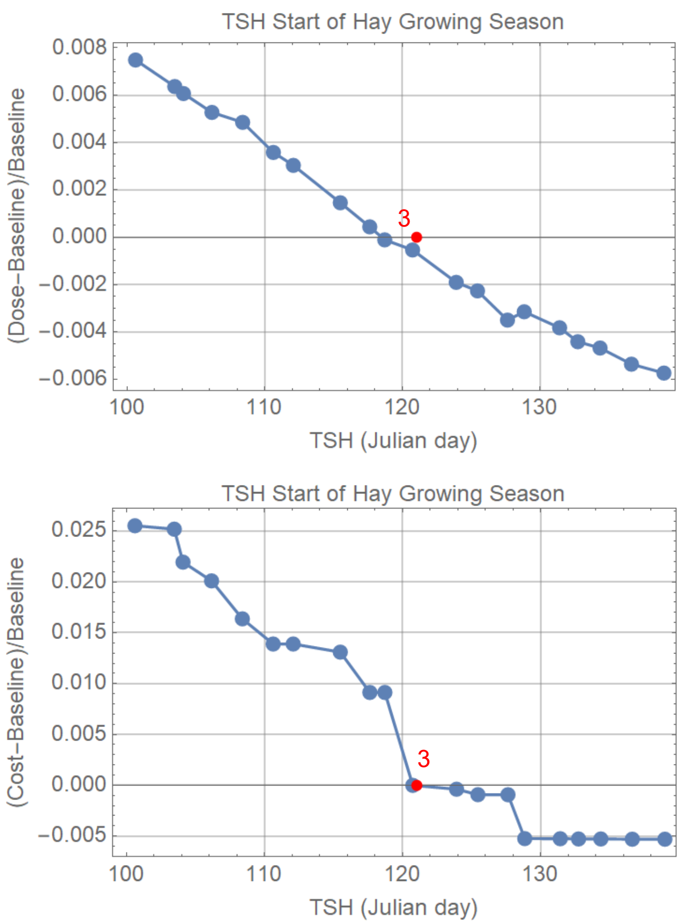


Figure 2-34. Relative change in population dose and economic cost versus the start of the hay growing season (TSH). The red dots is a relevant postulated accident date (other accident dates fall outside the domain of the scatter plots).

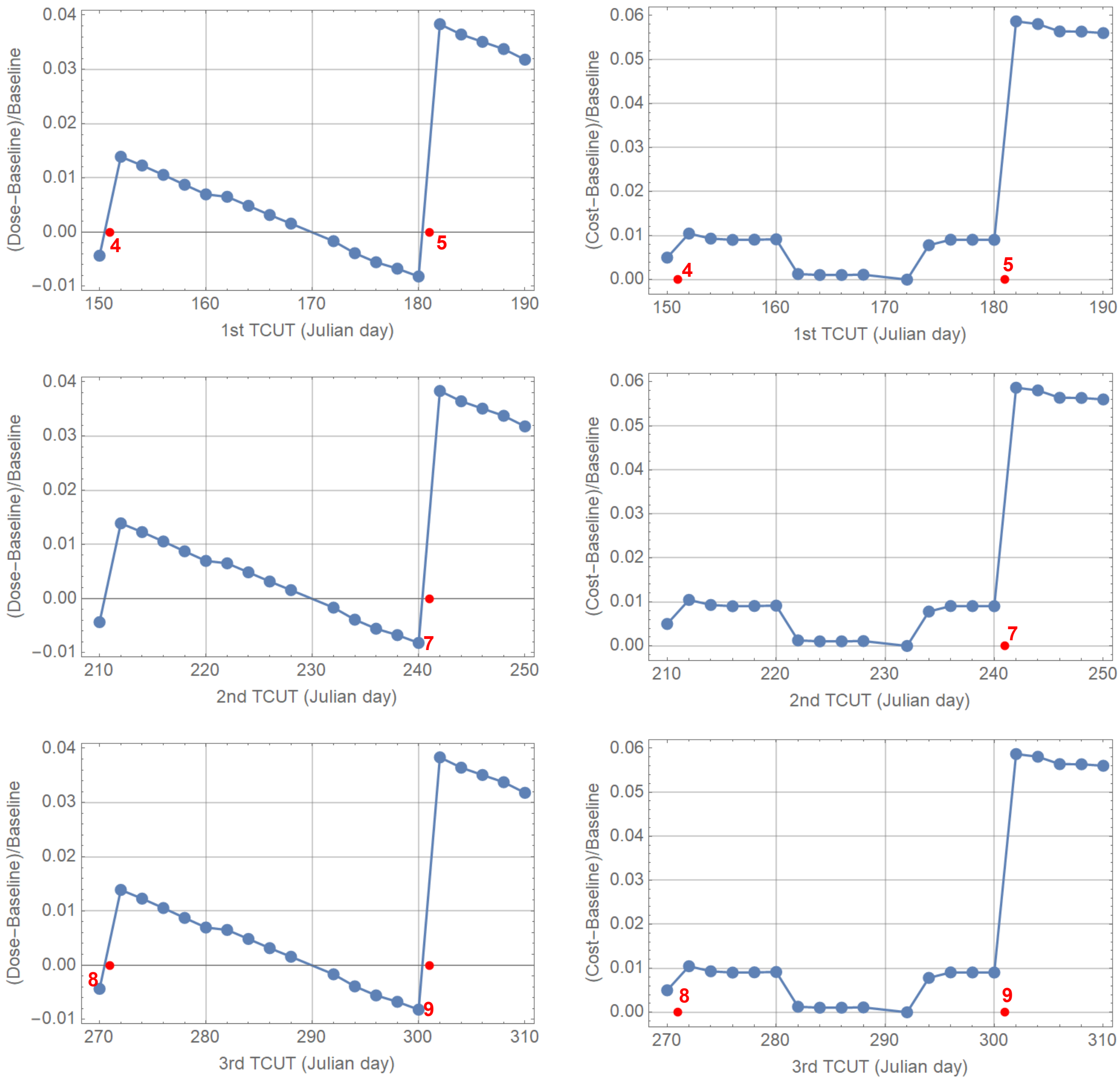


Figure 2-35. Relative change in population dose and economic cost versus the hay cutting dates, TCUT 1, TCUT 2, and TCUT 3. In the simulations, the three dates were simultaneously varied, with TCUT 2 = TCUT 1 + 60 days and TCUT 3 = TCUT 1 + 120 days. The red dots are relevant postulated accident dates (other accident dates fall outside the domain of the scatter plots); sharp jumps in the scatter plots coincide with specific accident dates.

2.5.5 Short-Term Integrated Milk Concentration (TINTM)

The COMIDA model includes a parameter defining the last day that dairy cows are on pasture from the date of the fallout event (TINTM). For example, if TI is the date of the event, the date of the last day that dairy cows feed on pasture is TI + TINTM. The COMIDA model uses such input to compute the short-term integrated milk concentration for the first accident year. It is used to evaluate benefits of restricting grazing immediately after a fallout event. Such input is not used in the population dose or the economic cost computations. As verification exercise, Figure 2-36 confirms that results are invariant to with respect to TINTM. Other outputs captured in the file tbl_outStat.txt are also independent of the parameter TINTM.

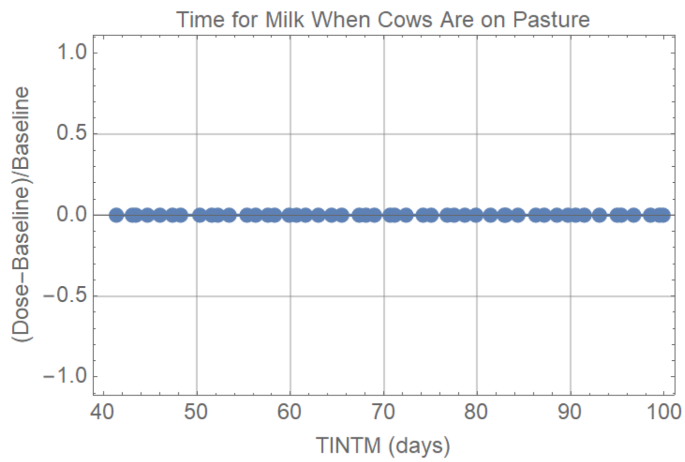


Figure 2-36. Relative change in population dose and economic cost versus the last day dairy cows graze (TINTM).

2.5.6 Time Parameter Inputs

The time parameters affect, for example, integration times to compute the amount of radioactivity from fallout incorporated in foodstuffs. The COMIDA model captures seasonal variability and computes consequences based on when the fallout event occurs. However, the sensitivity plots in Sections 2.5.1 to 2.5.4 indicate that changes in the duration of plant growing seasons or feeding seasons by themselves only have a secondary effect on the population dose and economic cost. The steepest changes occur not due to variations in the durations, but due to whether the beginning or end of a growing or feeding season occur near a postulated fallout event date. The most significant changes are associated with an event occurring shortly after the start of the crop growing season or shortly before the harvest date for crops (Figure 2-30). Near the baseline input values, and away from postulated accident dates, the population dose and the economic cost exhibit limited variability. Therefore, variation of the time parameters alone has limited effects on the consequence computations. The most important effect is captured by varying the postulated fallout event date throughout the year. The agricultural dates from the Sample Problem LNT input file are summarized in Table 2-11. The values in Table 2-11 are comparable to recommendations in NUREG/CR–6613 Volume 2 (Chanin et al., 1998, Volume 2, Section A.3.4), applicable for Bonneville County, Idaho (e.g., TSC=142 d, TEC=263 d, TSH=105 d, TSP=105 d, TSL=112 d, TEL=288 d). Values in Table 2-11 are preferred over recommendations in NUREG/CR–6613, for consistency with crop growth rates (ZKG) in Section 2.3.3.

Table 2-11. Time parameters defining duration of seasons and discrete events, from the Sample Problem LNT input file

COMIDA Variable	Value (day)	Comment
TT	65	Julian date for crop tillage (same date for all crops)
TSC	75	Julian date for the start of the growing season for five crops
TEC	290	Julian date for the harvest of five crops
TSH	120	Date for the start of the growing season for hay
TCUT	170, 230, 290	Up to three dates are input in COMIDA to define the cut time for hay. The radionuclide concentration in hay fed to animals is computed in COMIDA as the average of the three harvests.
TSP	110	Julian date that the pasture vegetation transitions from dormancy to active growth
TSL	111	Date of start of the grazing season for livestock
TEL	300	Date of end of the grazing season for livestock
TINTM	71	Number of the last day the dairy cows are on pasture after the initial contact of pasture with fallout. This input is used to compute concentration of radioactivity in milk during the first year after the fallout event, and not used in the computations of population dose and economic cost consequences. This parameter is an exploratory parameter to examine benefits of restricting grazing immediately after a fallout event.

2.6 Food Product Concentrations

The main outputs of the original COMIDA model are the radionuclide concentrations in food crops at the harvest time (Bq/kg) and the integrated animal product concentration (Bq-day/kg), both per unit of fallout for each radionuclide (Bq/m^2). The following sections discuss inputs related to the computation of radionuclide concentrations in crops and animal products.

2.6.1 Crop Concentrations at Harvest: Plant Deposition Factor (TVC), and Dry-to-Wet Mass Ratios (FD)

The total edible crop concentration at the harvest time is computed in the COMIDA model as (Abbott and Rood, 1993)

$$QC(\mathrm{TEC}) = \frac{Q_{vs}(\mathrm{TEC})\ \mathrm{TVC} + Q_{vi}(\mathrm{TEC})}{\mathrm{BMAX}}\ \mathrm{FD} \tag{2-23}$$

where

TEC	—	time of harvest
QC	—	total concentration in the edible plant for a specific radionuclide and human crop (Bq/m^2 per kg/m^2 = Bq/dry kg)
TEC	—	date of crop harvest
$Q_{vs}(\mathrm{TEC})$	—	concentration on the plant surface compartment for a specific radionuclide and human crop (Bq/m^2) at the time of harvest
$Q_{vi}(\mathrm{TEC})$	—	concentration on the plant edible tissues for a specific radionuclide and human crop (Bq/m^2) at the time of harvest
BMAX	—	Maximum plant edible biomass (dry kg/m^2)
TVC	—	plant deposition factor (unitless)
FD	—	ratio of dry-to-wet weight (unitless)

Based on intermediate outputs recorded in files of name ComidaN.cnc (N is the realization number, N=1, 2, 3, etcetera), it is inferred that in the COMIDA2 model, harvested products are

consumed during a 365-day period following the harvest, until the next harvest. Decay and ingrowth computations are applied to the food concentration during that 365-day consumption period. Therefore, the COMIDA2 computations implicitly assume a delay-to-consumption spread between 0 and 365 days. In updates to the MACCS and the COMIDA2 models it is recommended that the post-harvest decay of food concentrations be limited to the holdup time (the delay time from harvest to consumption), and not beyond. In reality, crops are harvested at multiple times, and fresh produce is consumed in a limited time (unless food is processed and preserved). The single harvest day assumed in the COMIDA2 model is intended to support computation of a reasonable concentration in food of radioactivity accumulated over the crop season.

Plant Deposition Factor (TVC)

The WinMACCS interface requires inputs for the parameters TVC and FD for the five crops. The parameter TVC (referred to as plant deposition factor in the WinMACCS interface) is a number between 0 and 1 to account for removal of surface contamination prior to ingestion (e.g., for removal of corn husks, 0 means full removal and 1 means no removal). The COMIDA model allows different values of TVC for the five crop categories. The sensitivity of the total dose and economic cost to the parameter TVC is displayed in Figure 2-37, around baseline values. For the sensitivity analysis, the TVC parameter was varied between 0.01 and 1 for all crops. The individual dose varies linearly with the parameter TVC, and the population dose tends to vary linearly with TVC. At high values of TVC (little to no contamination removal) in the case of grains, the extent of farm area interdiction increases (lower plot in Figure 2-37), increasing interdiction and total economic costs, and a corresponding decrease in the population dose. The population dose does not exhibit any variation with variation of TVC(leafy) because of the assumption that surface contamination is quickly incorporated into the vegetable tissues by translocation (see Section 2.4.6). In other words, in the case of leafy vegetables, it is assumed that the amount of surface contamination is negligible compared to contamination in the plant tissues.

Anomalous jumps in the population dose and economic cost were produced when TVC was set equal to 0 (full removal of surface contamination), possibly due to inappropriate handling of this limit case within the COMIDA2 code. It appears that setting TVC=0 must be avoided.

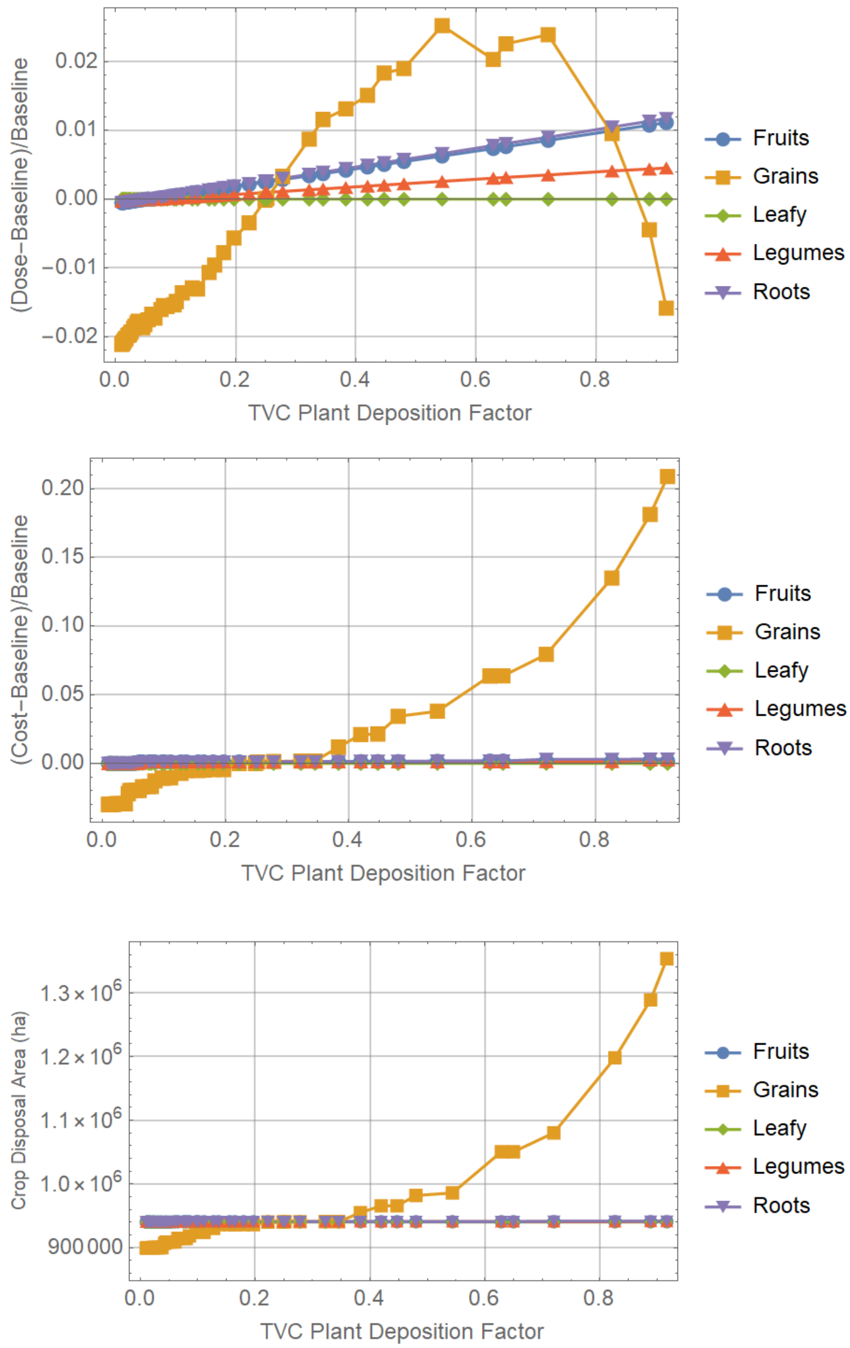


Figure 2-37. Relative change in population dose and economic cost versus the parameter TVC (contamination remaining factor), and crop disposal area versus TVC.

TVC Input Parameter Updates

Figure 2-37 indicates that population doses and economic costs monotonically increase with increasing values of the TVC, and that the effect is relatively small on the population dose and marginal on the economic cost, except for grains. Generic information to justify updates to the TVC parameter was not readily available, and it is recommended to adopt the NUREG/CR–6613 (Chanin et al., 1998, Volume 2, Section A.3.1) reproduced in Table 2-12.

Table 2-12. Plant deposition factor (TVC), based on NUREG/CR–6613 (Chanin et al., 1998, Volume 2, Section A.3.1)

COMIDA Variable	Crop	Value (days)
TVC	Grains	0.25
	Leafy vegetables	1.00
	Roots	0.05
	Fruits	0.05
	Legumes	0.05

Dry-to-Wet Weight Ratio (FD)

Figure 2-38 displays the relative change in the population dose and economic cost versus the normalized dry-to-wet ratios. To generate data to prepare Figure 2-38, the dry-to-wet ratios were varied from 0.01 to 1. It is highlighted that such domain of variability is likely exaggerated; physical variability is expected to be much narrower (e.g., grains have high FD and leafy vegetables have low FD). Constraining the domain of variability would reduce the sensitivity of the outputs to, for example, variation of FD(leafy vegetables).

As in the case of TVC, the common trend in the population dose and economic cost is a linear trend (reflecting the linear dependence of the individual dose on FD). The non-linear trends noted in the leafy vegetable and fruit curves are a consequence of the interdiction model. With increasing values of FD, the contaminant concentration of crops increases, increasing the extent of farm interdiction and crop disposal area (lower left-hand-side plot in Figure 2-38). In the case of leafy vegetables, the decreasing trend in the population dose correlates with increasing trends in the crop and milk disposal areas. The local maximum in the population dose versus FD(leafy) approximately coincides with the point at which the milk disposal area becomes an increasing function (lower right-hand-side plot in Figure 2-38).

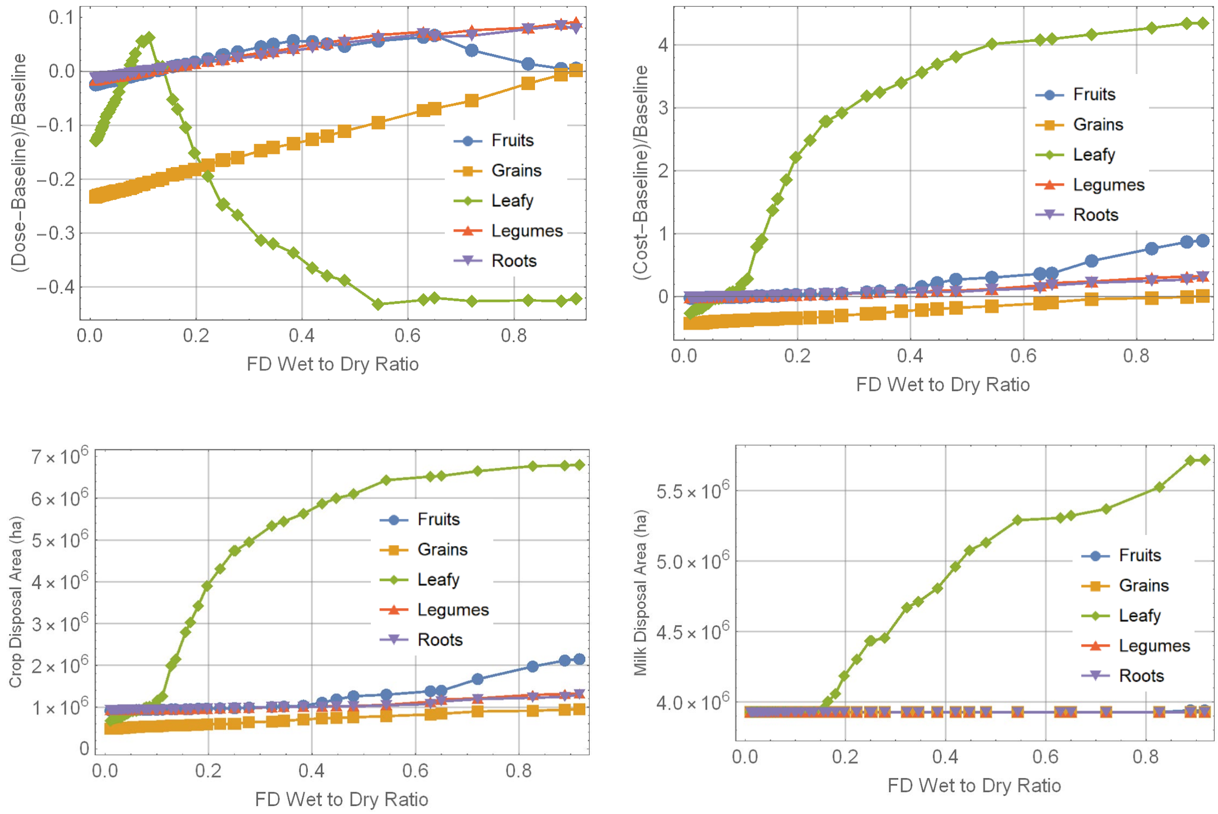


Figure 2-38. Relative change in population dose and economic cost versus the dry to wet ration (FD), and crop disposal and milk disposal versus FD.

FD Input Parameter Updates

Updates values of the dry-to-wet ratios (FD) are provided in Table 2-13.

Table 2-13. Updated dry-to-wet ratios, FD

Crop	Value	Comment/Reference
Grains	0.910	Beyeler et al., 1999, Table 6.77, grain; Bechtel SAIC, 2004b, p. 6-64
Leafy vegetables	0.070	Bechtel SAIC, 2004a, Table 6.2-1, leafy vegetables average
Roots	0.101	Bechtel SAIC, 2004a, Table 6.2-1, average of carrots and potatoes
Fruits	0.120	Bechtel SAIC, 2004a, Table 6.2-1, fruit average
Legumes	0.103	Bechtel SAIC, 2004a, Table 6.2-1, other vegetables average

2.6.2 Ingestion of Contaminants by Animals: Animal Feed Rates (DAIRY_RATE, BEEF_RATE, OTHER_RATE, POULTRY_RATE), and Delay Times for Animal Feed (THHAY, THGL)

The amount of contamination ingested by an animals, QA (Bq), during a year after the event (t_e = time of the event) is computed in the COMIDA model as

$$QA = \int_{t_e}^{t_e+365} R_a\, QP(t)\, dt \qquad (2\text{-}24)$$

where Ra is the rate of feed intake by an animal (kg/day) and QP is the animal feed concentration [Bq/kg]. The animal feed concentration (other than pasture) is the concentration at harvest [for example in the case of grains and legumes, Eq. (2-23)] corrected by additional decay and ingrowth beyond the harvest date. For pasture, the feed concentration is the instantaneous concentration. The integral in Eq. (2-24) is only a short notation for a complicated integral, with discrete intervals that account for example for the beginning and end of grazing season, the time of the fallout event, radionuclide decay and ingrowth, and a year measured after the time of the event. A similar integration approach is implemented in the COMIDA model for the second and successive years after the accident. The papers by Abbott and Rood (1993, 1994) should be consulted for details.

The COMIDA model considers beef cows, dairy cows, and other animals (e.g., dairy goats, dairy sheep, lambs, pigs, and egg-laying hens) consume pasture, hay, grain, legumes, and soil. Poultry chickens are assumed to consume grain, legumes, and soil. Independent ingestion rates, R_a, are defined for beef cows, dairy cows, other animals, and poultry chicken, for the different feed products and soil. The COMIDA model disregards any removal of contaminants from the soil compartments due to the ingestion of soil by the animals.

The WinMACCS interface allows to define inputs for animal feed rates R_a and delay times from storage to feed. A single delay time, THHAY, is input for hay for beef and dairy cows, and a different time, THGL, for all other animal feeds. The delay time is intended to account for temporal storage of feed products, accounting for radionuclide decay and ingrowth.

Holdup Times, Delay from Storage to Animal Consumption (THHAL, THGL)

The sensitivity of the total dose and the annual cost to the feed storage time (time from harvest to the animal consumption) is displayed in Figure 2-39. For the sensitivity analyses, the storage times were varied from 0 to 30 days. The dominant trends in the population dose versus the holdup time are decreasing trends; while the economic cost remains constant, except for transitions at specific values of the holdup time. The population dose versus THHAY exhibits transitions at approximately 4 days, 9 days, and 14 days, which correlate with transitions in milk disposal area (the milk disposal area transitions to a lower value at THHAY=4 days) and in the crop disposal area. The transition in the crop disposal area at 9 days is related to a transition to more condemned area and less decontaminated area at that time. An aspect of the COMIDA2 model that causes the condemned area and the crop disposal area to increase with increasing holdup time is related to the use of the holdup time to allocate the consumption of the harvest (first harvest after the accident) among the first and the second anniversaries of the accident. With increasing values of the holdup time, more of that first harvest is allocated to the second-year accident. The MACCS model compares the second-year accident individual dose to a user-defined dose limit (called DOSELONG in the WinMACCS interface) to trigger interdiction

actions (such as discarding crops and milk to mitigate radiation exposure) (Chanin et al., 1998, Volume 1, Section 7.10.1). Overall, the local effect of the holdup time on the population dose and total cost is minor to negligible in the baseline case. The holdup time constitutes a minor time component of the one-year cycle (from the accident anniversary to the next anniversary) over which modeled radionuclides accumulate and decay in animal tissues.

In updates to the COMIDA2 and MACCS models, it is recommended an option is included to disable the use of the holdup time to allocate consumption of the harvest among different accident years, to clearly separate radionuclide decay effects associated with the holdup time from those associated with accident timing.

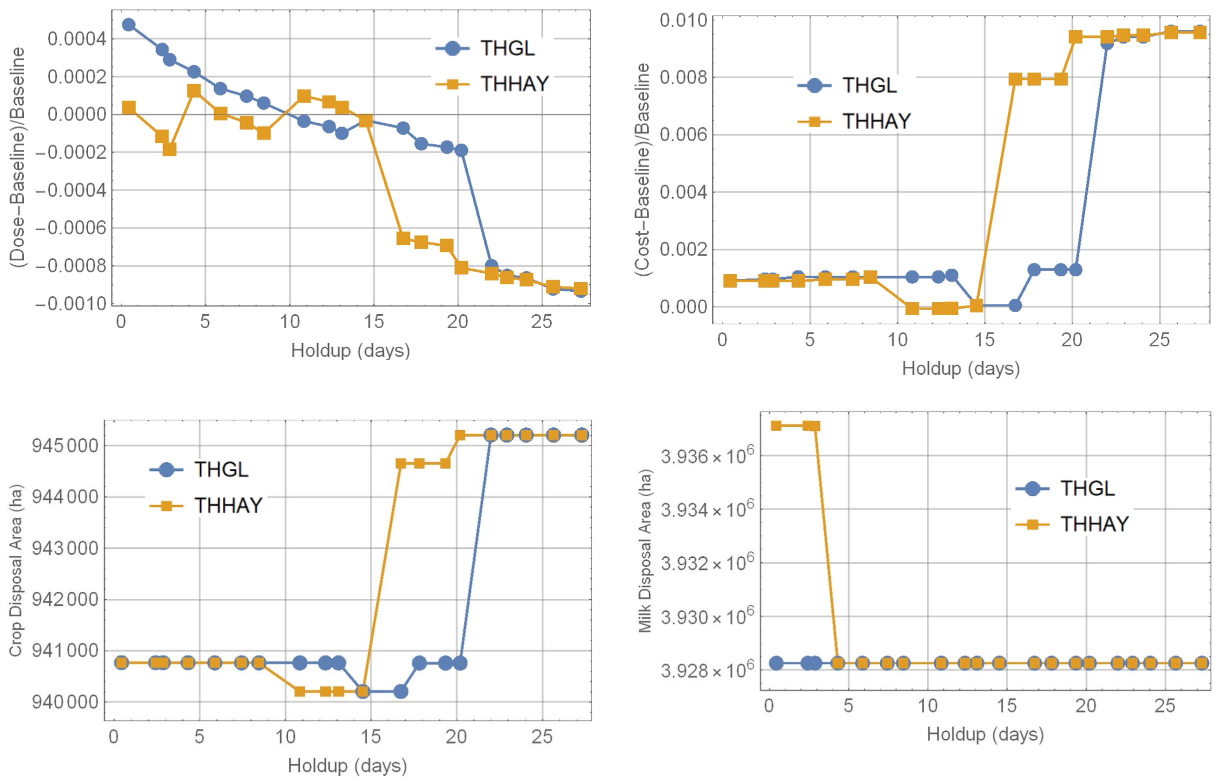


Figure 2-39. Relative change in population dose and economic cost versus the storage time (THHAY, THGL, delay time from harvest to animal consumption), and crop disposal and milk disposal areas versus THHAY and THGL holdup times.

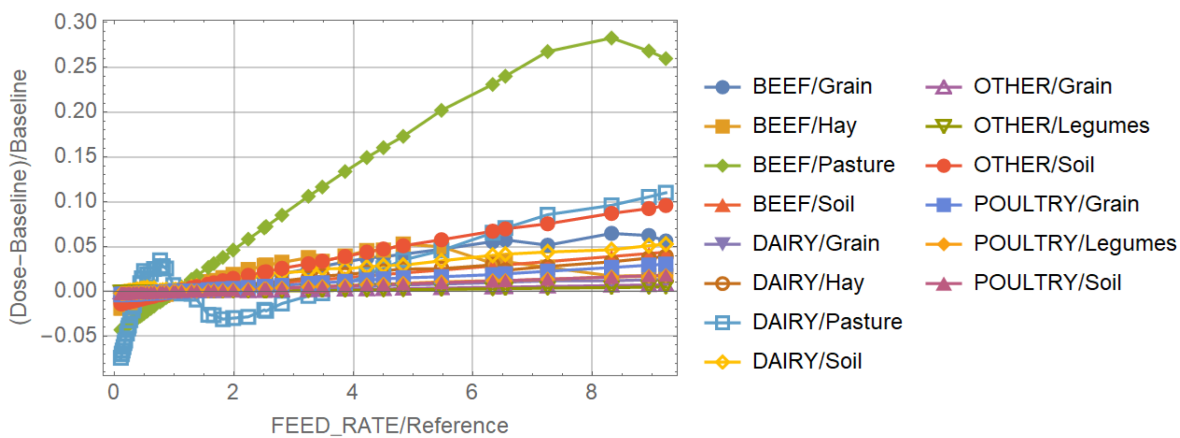
THGL, THHAY Input Parameter Updates

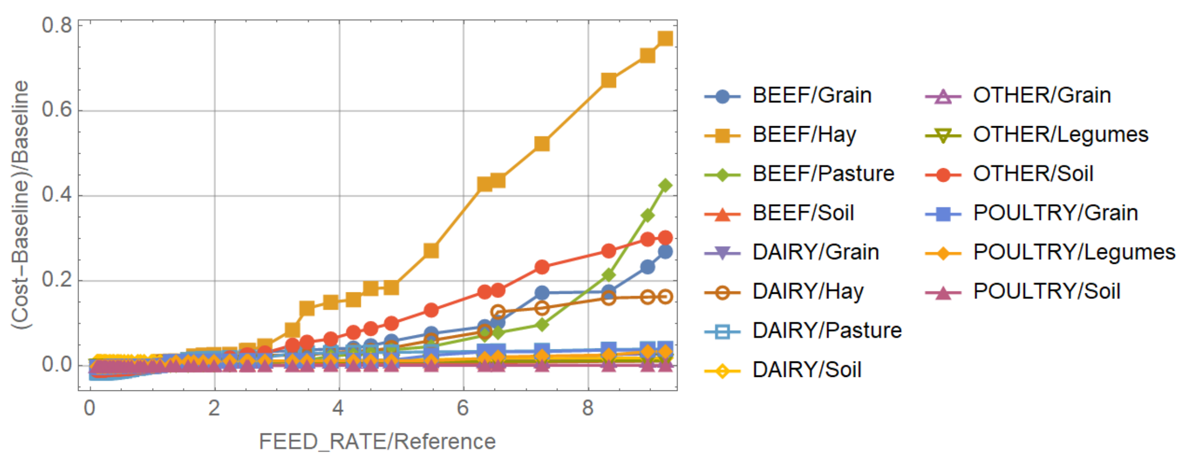
Regulatory Guide 1.109 (NRC, 1977) suggested 7 days for both THGL and THHAY. NUREG/CR–5512 Volume 3 recommends 14 days as holdup time for grains (Beyeler et al., 1999, Table 6.87). In the baseline case it was set THGL=THHAY=14 days, based in information by Beyeler et al. (1999, Table 6.87). After completing the sensitivity analysis and a more complete assessment of the COMIDA2 model, it is recommended to set THGL=THHAY=0. Note there is only one harvest date for crops, and there is already an implicit wait time in the COMIDA2 model associated from the assumed synchronization of the multiple harvests (i.e., the crop harvest is assumed to occur only until after all crops have matured). The additional THGL holdup time is considered redundant with the synchronization wait time. In the case of hay, with three harvest dates, livestock consumption of the hay is initiated only after the third harvest. Thus, the two earlier hay harvests have implicit animal consumption wait times, and the

additional holdup time THHAY is redundant at least for those two harvests (which constitute the majority of the hay production).

Feed Rates (DAIRY_RATE, BEEF_RATE, OTHER_RATE, POULTRY_RATE)

The sensitivity of the total dose and total cost to animal feed rates is shown in Figure 2-40. The individual dose increases linearly with the freed rate [per Eq. (2-24)]. Accordingly, under constant interdiction actions, the population dose linearly increases with increasing feed rates. The economic cost monotonically increases with increasing feed rate (second plot in Figure 2-40). The decreasing trend in the population dose versus cattle pasture feed rate, at high values of the feed rate, correlates with steeper increasing trends in the economic cost (second plot in Figure 2-40) and the crop disposal area (third plot in Figure 2-40). The irregular up-and-down-and-up trend in the population dose versus dairy cow pasture feed rate correlates to the response of the milk disposal area to variation of the pasture feed rate (fourth plot in Figure 2-40). The point of the local maximum dose (at around 0.5 of the baseline input—approximately 3.8 kg/day) coincides with the point at which the milk disposal area versus the pasture feed rate curve becomes steeper, and the point of the local maximum (at around 2 times the baseline input) coincides with the point at which the variation of the milk disposal area becomes less steep (fourth plot in Figure 2-40). Thus, the irregular up-and-down-and-up variation of the population dose versus the pasture feed rate can be explained on the basis of effects of the pasture feed rate on the milk disposal area.





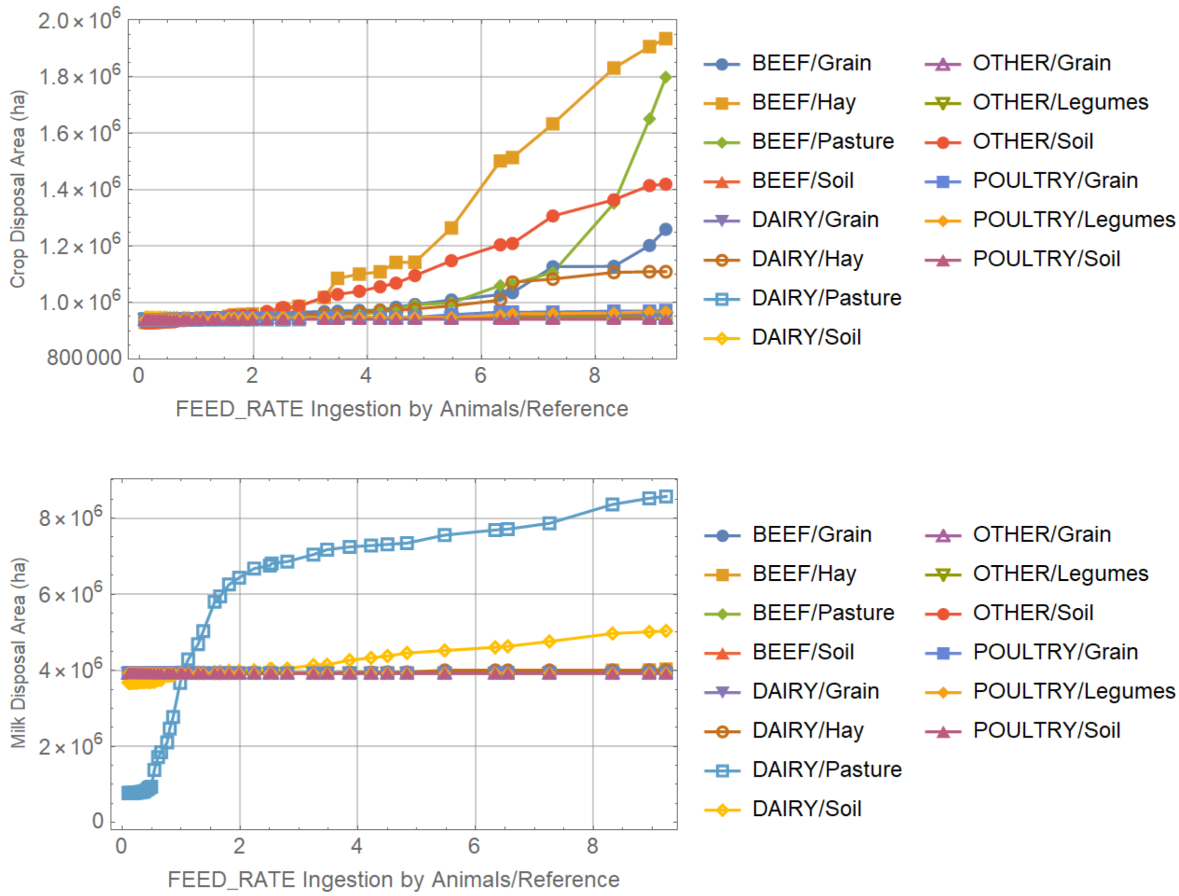


Figure 2-40. Relative change in population dose and economic cost versus animal feed rates (DAIRY_RATE, BEEF_RATE, OTHER_RATE, POULTRY_RATE), and crop disposal and milk disposal areas versus feed rates.

BEEF_RATE, DAIRY_RATE, OTHER_RATE, POULTY_RATE Input Parameter Updates

In defining the baseline inputs for the other animal category, it was assumed that the other animal was egg-laying hens. The justification is that egg is of common and frequent human consumption, and it is commonly available in general from local farm sources. Also, the transfer coefficient for relevant Cs and Sr isotopes is generally higher than for other protein alternatives, such as pork (in other words, given the same intake of contaminants by animals, eggs would have higher concentration of radioactivity than pork meats). The other animal category allows to input feed rates of pasture and hay; however, it was decided to restrict the grazing animals to cattle and dairy cows for the baseline input file. By contrast, the Sample Problem LNT input file defines the other animal category as a grazing animal, without specifying which animal it describes.

Feed rates are calculated based on the recommended total dry matter (TDM) intake for animals. NUREG/CR–6613 (Chanin et al., 1998) defined TMD intake for four animal categories, and within those animal categories the total dry matter is subdivided into feed fractions (types of feed for a given animal category). For dairy cattle, the TDM is multiplied with the recommended generic dairy cattle feed fractions to obtain feed rates of the dairy cow. Soil consumption rates equal to zero represent the case where animals are always kept indoors. If the dairy cows are

allowed outside to pasture, then the soil ingestion rate may be calculated considering the duration for the pasture season for milk cows. NUREG/CR–6613 defines independent feed rates for cattle used for beef products.

Poultry feed rates are split into three feed factions (grain, legumes, and soil). NUREG/CR–6613 (Chanin et al., 1998) states that in most regions the TDM consists primarily of grain for poultry and "other animals." The legume intake rate for both poultry and "other animals" is recommended to be set as 0 kg/day in NUREG/CR–6613. The soil ingestion rate for both poultry and "other animals" is recommended in NUREG/CR–6613 to be set as 0.01 kg/day and is based on Whicker and Kirchner (1987).

Updated animal feed rates are presented in Table 2-14. Bechtel SAIC (2004b, Table 6-38) includes more recent sources and cites several animal feed rates from multiple sources, for relevant COMIDA model animal categories. Wet intake rates from Bechtel SAIC (2004b, Table 6-38) were used to compute average values in the second column in Table 2-14. Rates in the third column, labeled TDM, were computed from the feed rates in the second column, and considering a wet-to-dry ratio equal to 0.25 [consistent with the midpoint of the range of 0.19 to 0.31, per IAEA (1994)]. Feed rates in columns Pasture, Hay, Grain, and Legumes in Table 2-14 were established from feed proportions by Beyeler et al. (1999, Section 6.4.6.3), and the rates in the TDM column. Feed rates in the Soil column in Table 2-14 are averages of soil ingestion rates in Bechtel SAIC (2004b, Table 6-38).

Table 2-14. Updated animal feed rates (kg dry/day), based on feed rates in Bechtel SAIC (2004b) and feed type proportions by Beyeler et al. (1999, Section 6.4.6.3)

COMIDA Variable	Total intake (kg wet/d)	TDM (kg dry/d)	Pasture* (kg dry/d)	Hay (kg dry/d)	Grain (kg dry/d)	Legumes (kg dry/d)	Soil (kg/d)
BEEF_RATE (beef cattle)	48.5	12.1	3.03	6.06	3.03	0	0.70
DAIRY_RATE (dairy cows)	61.5	15.4	7.69	6.15	1.54	0	0.95
OTHER_RATE (assumed egg-laying hen)	0.26	0.07	0	0	0.05	0.02	0.02
POULTRY_RATE (poultry)	0.26	0.07	0	0	0.05	0.02	0.02

The total wet intake in the second column corresponds to average values in Bechtel SAIC (2004b, Table 6-38). The Other wet intake was based on laying hen.

The total dry intake in the TDM column was computed from values in the second column, assuming and wet-to-dry ratio equal to 0.25.

Food intake proportions by Beyeler et al. (1999, Section 6.4.6.3) were used to compute the food intake distribution in the columns Pasture, Hay, Grain, and Legumes. The following proportions were considered:

- **Beef cattle**: 25% pasture, 50% stored hay, 25% stored grain
- **Milk cows**: 50% pasture, 40% stored hay, 10% stored grain
- **Poultry**: 75% stored grain, 25% fresh forage (assumed legumes for consistency of COMIDA model assumptions)
- **Other**: it was assumed that other animals correspond to laying-egg hen

Information in the Soil column correspond to averages computed from information in Bechtel SAIC (2004b, Table 6-38)

* Abbott and Rood (2004, p. 53) recommend correcting the daily average consumption of pasture to account for the grazing duration [thus correlating BEEF_RATE(pasture) and DAIRY_RATE(pasture) to the start (TSL) and end (TEL) of the grazing season]. Such correction/correlation was not implemented in the baseline inputs in this table.

Note that the COMIDA2 model assumes that feeds are uniformly consumed over a 365 day period, with the exception of pasture where the grazing season is of shorter duration (defined by the user by the parameters TSL and TEL, Section 2.5.3). Abbott and Rood (2004, p. 53) recommend correcting the daily pasture consumption rate (commonly inferred from annual consumption statistics) to account for a shorter duration of the grazing season than 365 days. However, this correction was not implemented in the baseline case. It is recommended, in updates to the COMIDA2 model that corrections are added to the daily pasture consumption rate. It is also recommended that user's are required to input average annual consumption rates for all animal feeds, to avoid ambiguities. For example, the COMIDA2 model should automatically adjust the daily pasture consumption rate (to match the user-defined annual pasture consumption), in case the user modifies the duration of the grazing season (via the parameters TSL and TEL, Section 2.5.3).

2.6.3 Radionuclide Concentrations in Animal Food Products: Transfer Coefficients (TC_BEEF, TC_MILK, TC_POULTRY, TC_OTHER), and Delay Times for Human Consumption (THBEEF, THMILK, THPOL, THOTHER)

The annual time-integrated radionuclide concentration per unit of mass, QAF (Bq-day/kg), for a specific animal product is computed as (Abbott and Rood, 1993, Eq. 18)

$$QAF = QA_T \, \mathrm{TC} \qquad (2\text{-}25)$$

where QA_T is the total radionuclide concentration ingested by an animal [QA is defined as in Eq. (2-24) in units of Bq, and a total value, QA_T, is computed by adding over all animal feed types], and TC (day/kg) is the radionuclide-specific transfer coefficient, which is the steady-state concentration in the animal product (Bq/kg) divided by the daily animal ingestion (Bq/day). The quantity QAF/365 days is interpreted as the daily average radionuclide concentration (Bq/kg) in the animal food product during the accident-year. The COMIDA code outputs concentrations in animal products at the accident anniversaries; which is equivalent to assuming that animals are slaughtered or harvested precisely at anniversaries of the accident (minus the holdup time). This approach maximizes the time-integrated radionuclide concentration in animal products. Those foodstuffs with maximal concentrations are assumed consumed throughout the accident year.

Transfer Coefficients (TC_BEEF, TC_MILK, TC_POULTRY, TC_OTHER)

Values of TC are input to the COMIDA model per radionuclide and per animal food type. Transfer coefficients are specified for beef (TC_BEEF), milk (TC_MILK), poultry (TC_POULTRY), and other animal products (TC_OTHER) (other type may represent pork and eggs, but in the baseline input file it was assumed that the other category corresponds to egg laying hen). Reported transfer coefficients in NUREG/CR–6613 (Chanin et al., 1998) are based on information in IAEA (1994) and a study by Baes et al. (1984). For the sensitivity analyses, for a single animal food type, the radionuclide inputs were perfectly correlated using the rank correlation function of WinMACCS. The results of the sensitivity analyses are shown in Figure 2-41. The individual dose is a linear function of the transfer coefficients. Accordingly, under constant or nearly constant interdiction actions, the population dose increases linearly with TC (top left-hand-side plot in Figure 2-41). A local maximum in the population dose versus TC(beef), and an irregular up-and-down-and-up trend in the population dose versus TC(milk) is displayed in the dose pot in Figure 2-41.

The explanation for those irregular trends is exactly the same explanation for irregular trends in the population dose versus the feed rate (see Figure 2-40 and explanatory text). Varying the transfer coefficient has a similar (but not identical) effect to varying the feed rate. The economic cost monotonically increases with increasing values of TC. The crop disposal area and the milk disposal area are provided for comparison to corresponding plots in Figure 2-40.

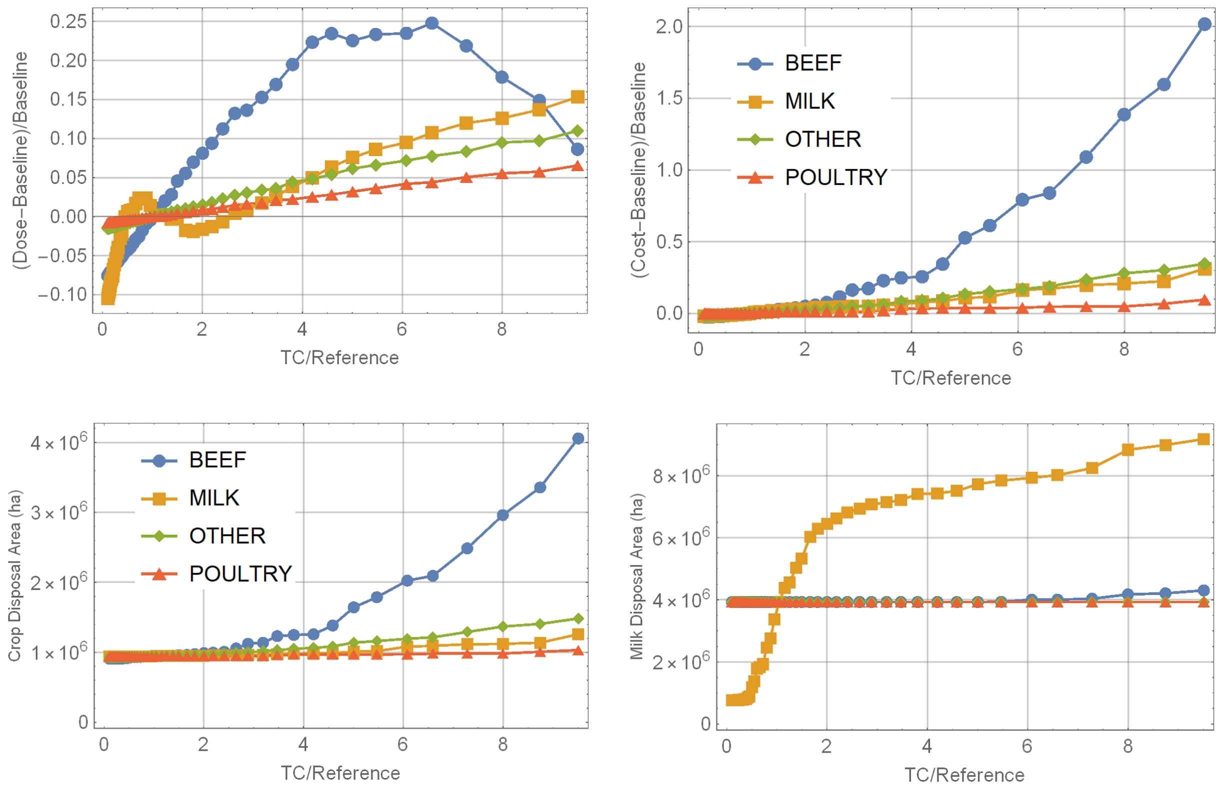


Figure 2-41. Relative change in population dose and economic cost versus the animal transfer coefficient (TC_BEEF, TC_MILK, TC_POULTRY, TC_OTHER), and crop disposal and milk disposal areas versus TC.

TC_BEEF, TC_MILK, TC_POULTRY, TC_OTHER Input Parameter Updates

Recommended values of TC are given in Table 2-15 and are based on more recent studies such as IAEA (2010); NUREG/CR–5512, Volume 1 (Kennedy and Strenge, 1992) and NUREG/CR–6825 (PNNL, 2003). The “Other” COMIDA category was assumed to correspond to egg-laying hen (see Section 2.6.2 for a justification of this assumption).

Table 2-15. Transfer coefficients for radionuclide transfer to beef (TC_BEEF), milk (TC_MILK), poultry (TC_POULTRY), and other (TC_OTHER)

Element	TC_BEEF (d/kg)	TC_MILK (d/L)	TC_POULTRY (d/kg)	TC_OTHER (d/kg)	Comment
Am	5.0×10^{-4}	4.2×10^{-7}	2.0×10^{-4}	3.0×10^{-3}	Beef: IAEA, 2010, Table 30. Milk: IAEA, 2010, Table 26. Poultry: Kennedy and Strenge, 1992, Table 6.18. Other: IAEA, 2010, Table 35 (eggs).
Ba	1.4×10^{-4}	1.6×10^{-4}	1.9×10^{-2}	0.87	Beef: IAEA, 2010, Table 30. Milk: IAEA, 2010, Table 26. Poultry: IAEA, 2010, Table 34. Other: IAEA, 2010, Table 35 (eggs).
Ce	7.5×10^{-4}	2.0×10^{-5}	1.0×10^{-2}	3.1×10^{-3}	Beef: Kennedy and Strenge, 1992, Table 6.18. Milk: IAEA, 2010, Table 26. Poultry: Kennedy and Strenge, 1992, Table 6.18. Other: IAEA, 2010, Table 35 (eggs).
Cm	5.0×10^{-4}	2.0×10^{-5}	4.0×10^{-3}	3.0×10^{-3}	Beef and Other: Assumed equal to Am, per PNNL, 2003, Section 4.13.17. Milk and Poultry: Kennedy and Strenge, 1992, Table 6.18.
Cs	2.2×10^{-2}	4.6×10^{-3}	2.7	0.4	Beef: IAEA, 2010, Table 30. Milk: IAEA, 2010, Table 26. Poultry: IAEA, 2010, Table 34. Other: IAEA, 2010, Table 35 (eggs).
I	6.7×10^{-3}	5.4×10^{-3}	8.7×10^{-3}	2.4	Beef: IAEA, 2010, Table 30. Milk: IAEA 2010, Table 26. Poultry: IAEA, 2010, Table 34. Other: IAEA, 2010, Table 35 (eggs).
La	1.3×10^{-4}	2.0×10^{-5}	0.10	9.0×10^{-3}	Beef: IAEA, 2010, Table 30. Milk, Poultry, and Other (eggs): Kennedy and Strenge, 1992, Table 6.18.
Pu	1.1×10^{-6}	1.0×10^{-5}	1.5×10^{-4}	1.2×10^{-3}	Beef: IAEA, 2010, Table 30. Milk: IAEA, 2010, Table 26. Poultry: Kennedy and Strenge, 1992, Table 6.18. Other: IAEA 2010, Table 35 (eggs).
Ru	3.3×10^{-3}	9.4×10^{-6}	7.0×10^{-3}	4.0×10^{-3}	Beef: IAEA, 2010, Table 30. Milk: IAEA, 2010, Table 26. Poultry: Kennedy and Strenge, 1992, Table 6.18. Other: IAEA, 2010, Table 35 (eggs).
Sr	1.3×10^{-3}	1.3×10^{-3}	2.0×10^{-2}	3.5×10^{-1}	Beef: IAEA, 2010, Table 30. Milk: IAEA, 2010, Table 26. Poultry: IAEA, 2010, Table 34. Other: IAEA, 2010, Table 35 (eggs).
Te	7.0×10^{-3}	3.4×10^{-4}	6.0×10^{-1}	5.1	Beef: IAEA, 2010, Table 30. Milk: IAEA, 2010, Table 26. Poultry: IAEA, 2010, Table 34. Other: IAEA, 2010, Table 35 (eggs).

Delay Times for Human Consumption (THBEEF, THMILK, THPOL, THOTHER)

The COMIDA2 model and the WinMACCS interface allow to define delay times, from food harvest (e.g., animal slaughter or milking) to human consumption. Delay times for four animal food types are input through the WinMACCS interface for beef (THBEEF), milk (THMILK), poultry (THPOL), and other animal products (THOTHER) (in the baseline case it was assumed that other category corresponds to egg-laying hen). The COMIDA2 model corrects radionuclide concentrations to account for decay and ingrowth during the holdup time, before human consumption of the animal food product. For the sensitivity analyses, the holdup time was varied from 0 to 30 days (Figure 2-42). The decreasing trends in the curves in Figure 2-42 arise from decreasing individual doses with increasing values of the holdup time due, partially due to

radionuclide decay and partially due to the use of the holdup time to allocate the consumption of the food products in the current and the next accident year (Chanin et al., 1998, Volume 2, Section 2.1.3.2). The economic cost, crop disposal area, and milk disposal area consistently decrease with increasing holdup times. The local maximum versus THMILK is a consequence of the interdiction model. The milk disposal area decreases with increasing THMILK, which increases the circulation of contaminated milk among the population and higher population doses. At higher values of THMILK, the milk disposal area reaches a plateau, and the population dose becomes a decreasing function of THMILK, due to decreasing individual doses and radionuclide decay.

In updates to the COMIDA2 model, it is recommended that a logical (true/false) input is included to enable/disable the use of the holdup time in allocating the amount of food intake in the current and the next accident year, to be able to distinguish holdup time decay effects from accident timeline effects.

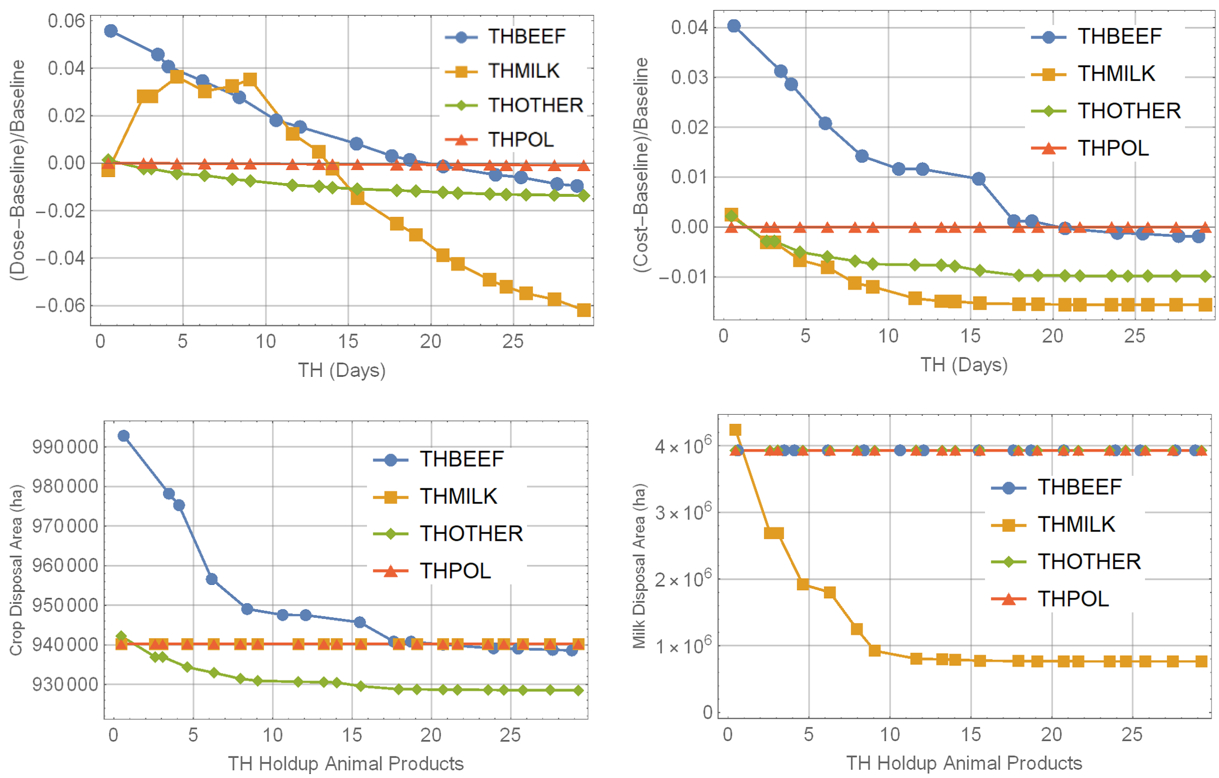


Figure 2-42. **Relative change in population dose and economic cost versus the food storage time (THBEEF, THMILK, THPOL, THOTHER, delay time from production to human consumption), and crop disposal and milk disposal areas versus TH.**

THBEEF, THMILK, THPOL, THOTHER Input Parameter Updates

Regulatory Guide 1.109 (NRC, 1977) suggests 4 days for THMILK and 20 days for THBEEF, THPOL, and THOTHER (NRC, 1977). More recent documents (e.g., NUREG/CR–5512, Beyeler et al., 1999, Table 6.87) include information on holdup times. Updated values in Table 2-16 are based on information in NUREG/CR–5512 (Beyeler et al., 1999, Table 6.87).

Table 2-16. Delay time for human consumption of animal products, based on information by Beyeler et al. (1999, Table 6.87)

COMIDA Variable	Value (days)
THBEEF	20
THMILK	1
THPOL	1
THOTHER	1

2.7 Individual Dose and Population Dose: Consumption Rates (CONSUM_RATES), Production Rates (PRODUC_RATES), Contamination Reduction Factor (PROCLOSS) and Human Consumption Delay Times (HOLDUPTM)

Individual and collective or societal doses are computed in the COMIDA2 model, extending the computations of the original COMIDA model. The individual dose calculations in COMIDA2 are based on an approach defined by Abbott and Rood (1993, pp. 33-34).

2.7.1 Mathematical Model for Individual Dose and Population Dose

For any food product (plant or animal origin food product) and any radionuclide, COMIDA outputs the radionuclide concentration (Bq/kg) per unit of fallout (Bq/m^2), denoted as QTC_f (the index f stands for a specific food product). The individual annual dose to organ k, from foodstuff f is computed as [Abbott and Rood, 1993, Eq. (25)]

$$D_{fk} = GC\ FP_f\ DF_k \int_0^{tc_f} QTC_f(t)\ R_f\ dt \qquad (2\text{-}26)$$

where

D_{fk}	—	dose to organ k from consumption of food product f (Sv) over a consumption period tc (annual dose to organ k)
GC	—	initial radionuclide ground concentration (Bq/m^2) (fallout intensity)
QTC_f	—	average concentration in foodstuff f per unit of fallout output by COMIDA (Bq/kg/Bq/m^2)
R_f	—	average individual ingestion rate of foodstuff f (kg/day)
FP_f	—	radioactivity fraction remaining in foodstuff f after food processing (dimensionless). Symbolized as PROCLOSS in the WinMACCS interface
DF_k	—	dose conversion factor for organ k (Sv/Bq)
tc_f	—	human consumption period for foodstuff f over the year (365 days)

The term QTC_f is computed differently for plant or animal food products, and both are the output of the original COMIDA model. In the case of plant products, the concentration QTC_f is the concentration at the time of harvest [concentration in Eq. (2-23) normalized by the unit fallout intensity]. The integral in Eq. (2-26) is a shortcut notation for a more complex computation accounting for decay and ingrowth during the delay time for consumption after harvest (HOLDUPTM). The COMIDA2 model allows specification of five delay times associated with the five crop categories. According to NUREG/CR–6613, Volume 2 (Chanin et al., 1998, Volume 2, Section 2.1.3.2), the holdup times are restricted to a maximum of 60 days. The time HOLDUPTM is also accounted to define the proportions of crops consumed during the accident year and the following accident year (Chanin et al., 1998, Volume 2, Section 2.1.3.2). As stated

before, the computations associated with HOLDUPTM are part of the updated COMIDA2 model, and not included in the original COMIDA model by Abbott and Rood (1993, 1994).

In the case of animal products, the concentration QTC_f is defined as

$$QTC_f = 1\text{Bq}^{-1}\text{m}^2 \frac{QAF_f}{365 \text{ days}} \tag{2-27}$$

where QAF_f is the yearly average concentration (annual average concentration with the year starting at the time of the fallout event) defined by Eq. (2-25). The term QAF_f includes decay and ingrowth corrections accounting for a delay time (holdup time) from animal slaughter to the time of human consumption (Section 2.6.2; Abbott and Rood, 1993, p. 35). For animal products, the concentration QTC_f is a daily average concentration during the accident-year; and the integral in Eq. (2-26) is simply a multiplication by the time period tc_f (=365 days). The updated COMIDA2 model implements an additional correction accounting for the delay time for human consumption of animal products (TH, Section 0), proportioning the food of animal origin to be consumed in the current accident year and the following accident year (see Chanin et al., 1998, Volume 2, Section 2.1.3.2, for some details).COMIDA2 includes a factor FP_f, symbolized as PROCLOSS in the WinMACCS interface, to account for removal of inventory due to food processing. Individual factors are defined for all food types. This factor should not be confused with the factor TVC [Eq. (2-23), Section 2.6.1], referred to as plant deposition factor, which applies to removal of contamination on plant surfaces. On the other hand, the factor PROCLOSS is intended to account for general removal of radioactivity, both in plant internals and surfaces.

The interdiction model is enabled based on the levels of food contamination. The interdiction model includes actions related to interdiction (temporarily suspending farm production and destroying farm products), land condemnation, land decontamination, and milk disposal. Different actions may be triggered depending on individual doses and contamination levels; those actions help lowering the population dose but with additional economic costs. The interdiction model in COMIDA2 corrects the dose computation to account for remedial actions (e.g., food impoundment, land condemnation, land decontamination, and milk disposal), and outputs an effective dose per unit of food mass per unit of fallout for each radionuclide j, DS_j (Sv/kg/Bq/m^2). The population or societal dose is computed as (Chanin et al., 1998, Volume 2, pp. 2-4)

$$D_S = A \sum_{j=1}^{N} \sum_{f=1}^{F} GC_j \, DS_j \, AP_f \tag{2-28}$$

D_s	—	societal annual dose (person-Sv)
N	—	number of radionuclides
F	—	number of food products
A	—	area of the spatial element (m^2)
GC_j	—	fallout concentration for radionuclide j (Bq/m^2)
DS_j	—	COMIDA2 societal dose-to-source ratio for nuclide j (Sv/kg/Bq/m^2)
AP_f	—	annual production rate of foodstuff f (kg/m^2)

The COMIDA2 WinMACCS interface allows to define inputs for the individual consumption rate, R_f (kg/yr), the food processing radioactivity removal factor FP_f = PROCLOSS, the annual production rate AP_f, and the holdup time (HOLDUPTM).

2.7.2 Contamination Reduction Factor (PROCLOSS)

For the sensitivity analysis, the PROCLOSS was varied between 0 and 1 (0 means full removal, and 1 means no removal) for nine food products (Figure 2-43). For the majority of the food products, the population dose increases linearly with increasing values of PROCLOSS (also displayed in the expanded vertical scale plot in Figure 2-43). The interdiction model causes irregular trends [e.g., population dose versus PROCLOSS(milk) in Figure 2-43], due to competing effects from interdiction, decontamination, and condemnation. The lower right-hand-side plot in Figure 2-43 includes the variation of the milk disposal arear versus PROCLOSS: the milk disposal area increases with increasing values of PROCLOSS(milk). The economic cost is weakly dependent on PROCLOSS, except for leafy vegetables and grains. The economic cost monotonically increases with increasing values of PROCLOSS for all food products.

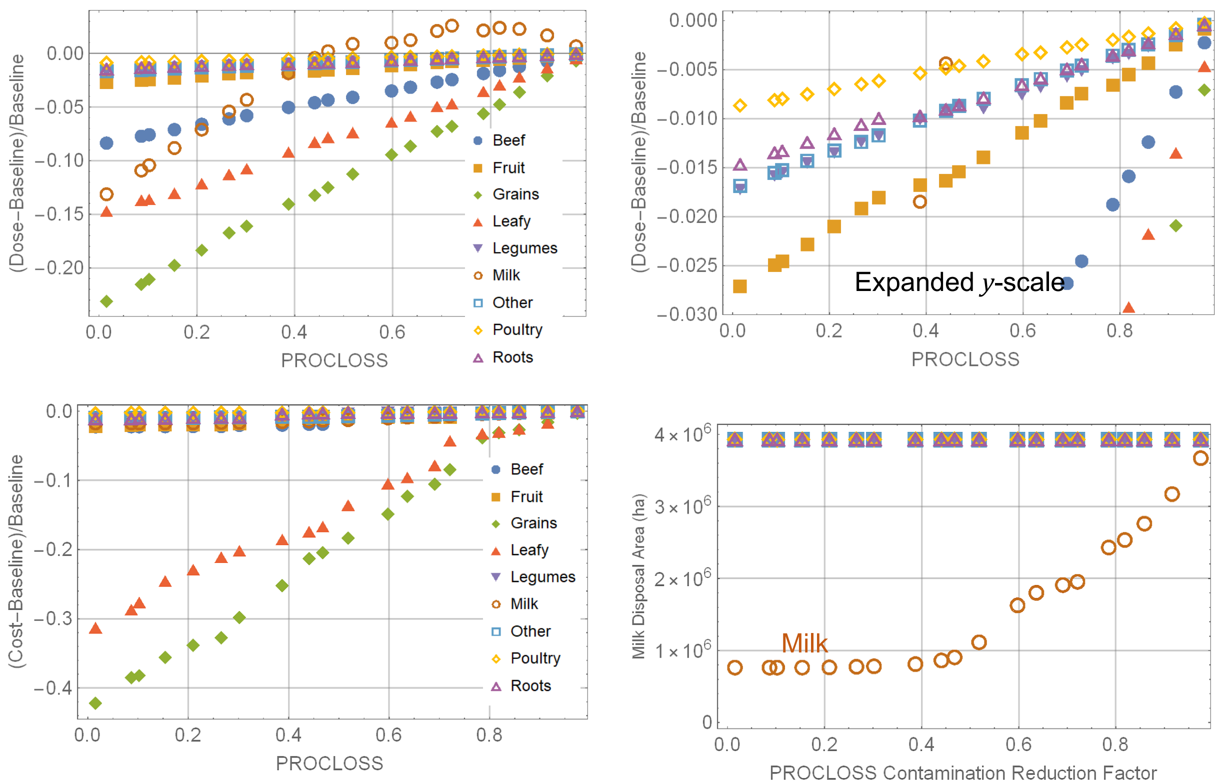


Figure 2-43. Relative change in population dose and economic cost versus the radioactivity fraction remaining after food processing (PROCLOSS), and milk disposal area versus PROCLOSS.

PROCLOSS Updated Input Value

It is recommended to set PROCLOSS=1 for animal food products (beef, milk, other, poultry), and not take credit for removal of radioactivity from food processing, which tends to overestimate individual doses. The parameter PROCLOSS for plant products is of similar definition to the plant deposition parameter TVC. The sensitivity of the dose and the cost to the parameters PROCLOSS and TVC is similar (in the absence of interdiction model effects), but the PROCLOSS is slightly steeper. It is recommended to set PROCLOSS = 1 (no radioactivity removal due to food processing), and account for removal of radioactivity from plant surfaces through the plant deposition parameter TVC.

2.7.3 Crop Consumption Delay Times (HOLDUPTM)

The sensitivity of the population dose and total cost to the holdup time (HOLDUPTM) is displayed in Figure 2-44. The effect of holdup time on the population dose and economic dose consequences is difficult to anticipate. Competing effects are at play regarding radionuclide decay, ingrowth, and the use of HOLDUPTM in the COMIDA2 model to proportion crop product consumption at a particular accident year and the following year. Figure 2-44 shows that the decreasing trends in the population dose versus HOLDUPTM (grains and leafy vegetables) are correlated to increasing trends in the total economic cost and interdicted farm area. The increasing trend in interdiction actions with increasing values of HOLDUPTM is an artefact of the use of HOLDUPTM in the COMIDA2 model to allocate the harvest consumption among the current accident year and the next accident year (Chanin et al., 1998, Volume 2, Section 2.1.3.2). The highest calculated concentration of radioactivity is present in the first harvest following the accident. The first harvest is consumed during the first and second years after the accident. The HOLDUPTM is included in equations that allocate the harvest consumption among the first two years. With increasing values of HOLDUPTM, more of the first harvest is consumed during the second accident year (and less during the first accident year). The MACCS model compares the second accident year individual dose to a user-defined dose limit (a parameter named DOSELONG in WinMACCS) to trigger actions such as farm interdiction (Chanin et al., 1998, Volume 1, Section 7.10.1). This explains the increasing trends (grains and leafy vegetable curves) in the farm interdiction versus the holdup time in Figure 2-44.

The expanded vertical scale population dose plot in Figure 2-44 indicates that with relatively constant interdiction actions, the population dose decreases with increasing holdup time. This result is partially explained by decreases in the individual dose from radionuclide decay and the decreases in the proportion of the first harvest consumption during the first accident year with increasing values of the holdup time.

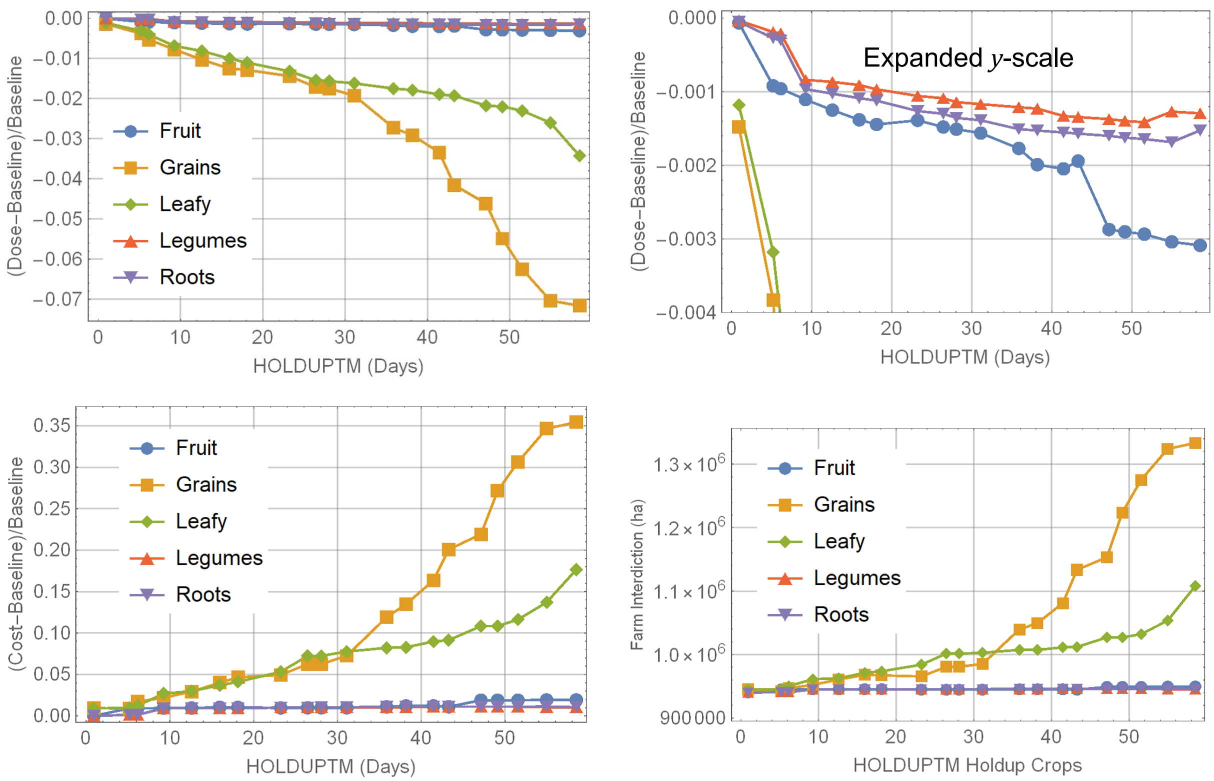


Figure 2-44. Relative change in population dose and economic cost versus the holdup time (HOLDUPTM, delay from harvest to consumption), and farm interdiction area versus HOLDUPTM.

In updates to the COMIDA2 model, it is recommended that a logical (true/false) input is added to enable/disable the use of the holdup time to allocate the consumption of the initial harvest among the first or second accident years, to clearly separate holdup and decay effects from other effects.

HOLDUPTM Input Parameter Updates

It is recommended to set HOLDUPTM=0 for the crop products, in consistency with NUREG/CR–6613 Volume 2 (Chanin et al., 1998, Volume 2, Section 2.5.1).

It is noted that COMIDA2 uniformly spreads the consumption of a harvest over 365 days, with decay corrections over the entire period. This is equivalent to assuming holdup times range between 0 and 365 days. For future updates to the MACCS code, it is recommended that the application of decay corrections is reconsidered. Decay corrections should be constrained to the holdup time defined by the HOLDUPTM input, and not beyond. The COMIDA2 model is an approximated model that does not account for several harvests during the year and consumption of food products shortly after those harvests. Considering consumption of a single harvest spread over a whole year, and the application of decay over that year to reduce crop food concentrations, may underestimate consequences, especially consequences associated with shorter lived radionuclides.

2.7.4 Consumption Rates (CONSUM_RATES) and Production Rates (PRODUC_RATES)

The sensitivity of the population dose and total cost to the individual consumption rates is displayed on Figure 2-45, which also includes plots of the crop disposal area and milk disposal area versus the consumption rates. The individual dose increases with increasing consumption rates, which tends to increase the extent of interdiction actions and economic costs. Figure 2-45 shows that the decreasing population dose with increasing CONSUM_RATES is related to increasing economic cost and crop disposal area. In the specific case of milk consumption rates, the different trend in the population dose is related to the different trend in the milk disposal area.

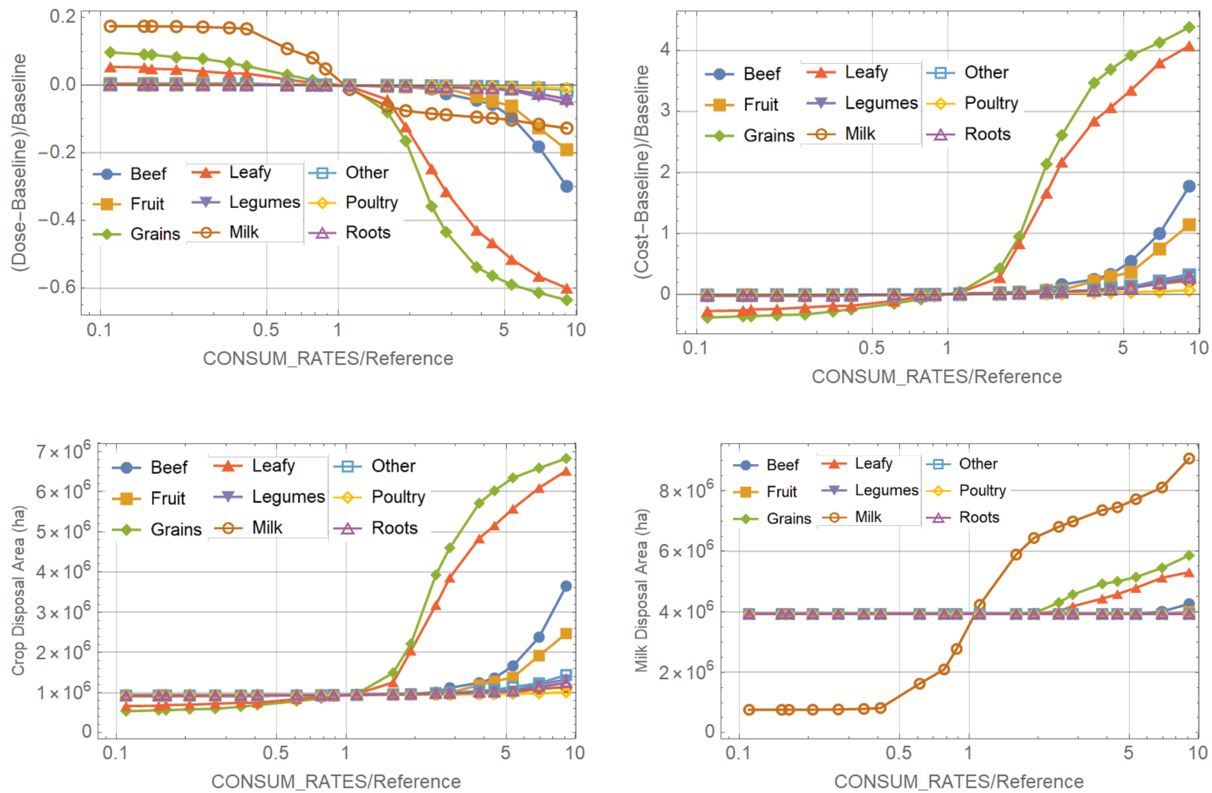


Figure 2-45. Relative change in population dose and economic cost versus the individual consumption rate (CONSUM_RATES), and crop disposal and milk disposal areas versus the consumption rates.

Finally, the sensitivity of the population dose and the total cost to the food production rates are shown in Figure 2-46. The population dose is linearly proportional to the food production rate AP_f [Eq. (2-28)]. On the other hand, the total cost is independent of the food production rate (interdiction actions are triggered by individual doses and individual consumption rates, and not by societal food production rates).

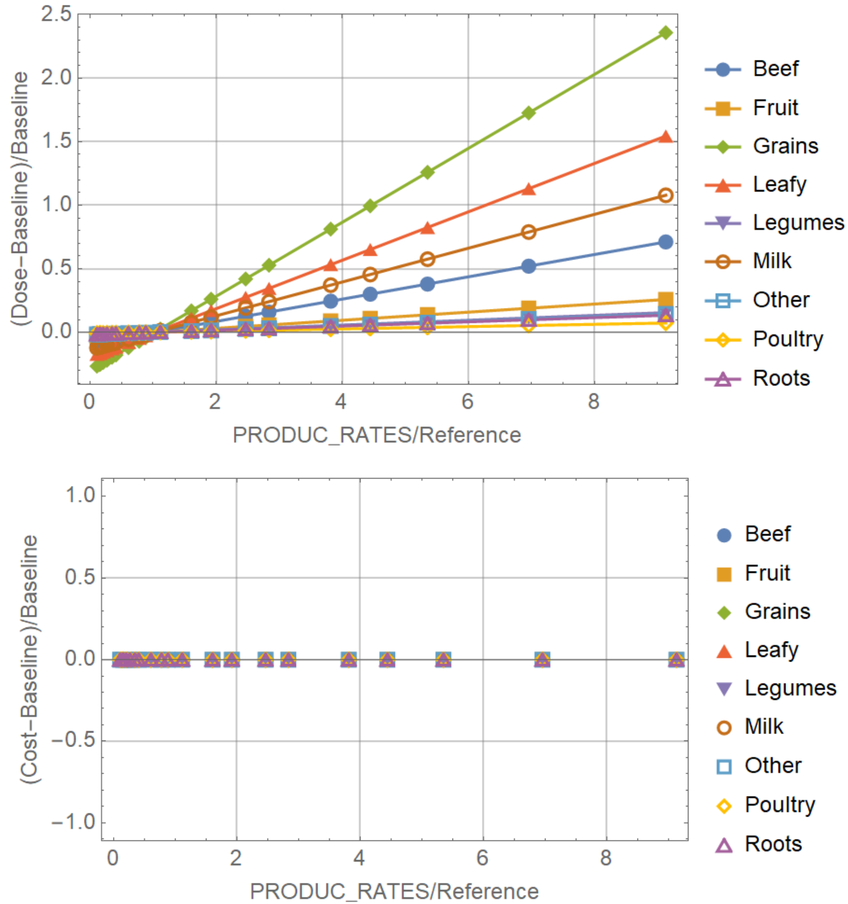


Figure 2-46. Relative change in population dose and economic cost versus the food production rate (PRODUC_RATES).

CONSUM_RATES and PRODUC_RATES Input Parameter Updates

Updated values for consumption rates in Table 2-17 for plant products (except legumes) are based on information in the Agricultural and Environmental Input Parameters for the Biosphere Model (Bechtel SAIC, 2004a, Table A-4), which examined statistics from a 1999 U.S. Department of Agriculture report of commonly eaten plants, and estimated national consumption averages (total food production minus non-consumptive uses including exports divided by the total population size). Consumption rates of animal products and legumes is based on NUREG/CR–5512 Volume 1 (Kennedy and Strenge, 1992, Table 6.15). NUREG/CR–6613 Volume 2 (Chanin et al., 1998, Volume 2, Table 3) includes an example of consumption rates for exploratory purposes, which should not be interpreted as “recommended” or “endorsed” inputs. Those exploratory values are relatively similar to values in Table 2-17, with a total individual annual consumption rate of 405 kg. Alternative consumption rates are available in a report by Electric Power Research Institute (EPRI) (Smith et al., 1996, Table 3-7), with national consumption rates for a few different countries including United States. However, there are significant divergences of data in the EPRI report with respect to data in Table 2-17 (e.g., the annual consumption rate of milk is 230 kg/yr; the total consumption of plant products is 291 kg/yr in the EPRI report versus 200.5 kg.yr in Table 2-17), and the original sources are not clearly defined. A report prepared by Bechtel SAIC (2000, Table 3), compiled consumption rates in Amargosa Valley, based on surveys, accounting for locally produced food, and differentiating farmers from common residents. In that case, the consumption rates of locally produced foods

were much lower than in Table 2-17 (e.g., the Amargosa Valley annual consumption of locally grown plant products by residents was 14.6 kg/yr versus approximately 200 kg in Table 2-17; the milk consumption in Amargosa Valley by residents was only 4.14 L/yr), due to desertic conditions requiring importing foods. The example by Bechtel SAIC (2000, Table 3) suggests that consumption rates based on national averages (such as those in Table 2-17) may overestimate the consumption rates of locally produced food products in general, which may lead to individual dose overestimates. The user guide NUREG/CR–6613 Volume 2 (Chanin et al., 1998, Volume 2, Section 2.2.1) refers to NRC Regulatory Guide 1.109 for consumption rates of maximally exposed individuals, but contrasts the total consumption of 940 kg/yr versus less than half in other sources, suggesting that the NRC guide overestimates consumption rates.

For the annual production rates, the approach suggested by Chanin et al. (1998, Volume 2, Section 2.2.2) was followed: one person is fed by the outcome of 10^4 m^2 of farmland. The 10^4 m/person round number was estimated from the total farm area in the US (considering 67 percent of the land is devoted to domestic consumption) divided by the total population (from the 1990 census), which is consistent with estimates from other authors (e.g., Abbott and Wenzel, 1994). The corresponding annual production rates are listed on the third column in Table 2-17.

Table 2-17. Updated annual consumption rates (CONSUM_RATES) and annual production rates (PRODUC_RATES), for individual and societal dose computations, assuming one person is fed per 10,000 m^2 of farmland.

Product	CONSUM_RATES (kg/yr)	PRODUC_RATES (kg/m^2)	Comment/Reference
Grains	82	0.0082	Bechtel SAIC, 2004a, Table A-4. Total of wheat flour, corn, oat, and barley
Leafy vegetables	25	0.0025	Bechtel SAIC, 2004a, Table A-4. Total of lettuce head, cabbage, lettuce leaf, celery, broccoli, cauliflower, asparagus, spinach
Roots	27	0.0027	Bechtel SAIC, 2004a, Table A-4. Total of potatoes and carrots
Fruits	41	0.0041	Bechtel SAIC, 2004a, Table A-4. Total of melons, tomatoes, apples, grapes, peaches, strawberries, pears, and plums and prunes
Legumes	25.5	0.0026	Kenedy and Strenge, 1992, Table 6.15, 0.5 of Other vegetables entry
Beef	59	0.0059	Kenedy and Strenge, 1992, Table 6.15
Milk	100	0.0100	Kenedy and Strenge, 1992, Table 6.15
Poultry	9	0.0009	Kenedy and Strenge, 1992, Table 6.15
Other	10	0.0010	Kenedy and Strenge, 1992, Table 6.15, Eggs entry
Total	**378.5**		

Implicit in the numbers in that third column is the assumption of uniform productivity per land for all agricultural products. Chanin et al. (1998, Volume 2, Section 2.2.2) note that such assumption overestimates the animal productivity, which requires more land, possibly an order of magnitude more than land for crops. Chanin et al. (1998, Volume 2, Section 2.2.2) advise against using yield rates (e.g., BMAX, Section 2.3 in this report) and farmland areas to estimate productivity rates, because BMAX includes product that is wasted, fed to animals, fallow amounts, and not locally consumed. A labor-intensive approach to estimate site-specific consumption and productivity rates that are balanced would require surveys and identification of locally produced food amounts, the total number of individuals feeding from defined agricultural areas, and the size of the areas devoted to the various agricultural activities, gathered over

several years to average year to year variability. Note, however, that the COMIDA2 model does not strictly require balance between consumption and production rates. If the system is imbalanced (for example, the production rate includes exported food), then population doses may reflect consequences occurring outside of the grid modeled in MACCS, requiring appropriate and careful interpretation by users.

3 SENSITIVITY ANALYSIS SUMMARY AND CONCLUSIONS

As stated in the introduction, for the one-at-a-time input parameter variation runs, the majority of the parameters were varied by two orders of magnitude centered around baseline values. Exceptions in the two -order-of-magnitude variation were agricultural dates and some parameters representing fractions between 0 and 1. It is highlighted that a two-order-of-magnitude variability may exceed the domain of physical variability for some input parameters. Exceeding the physical domain was intended to explore the mathematical meaning of input parameters and the mathematical structure of the COMIDA2 model. Some steep local sensitivities arise due to the use of exaggerated domains of variability of input parameters.

To prepare spider or sensitivity plots, the parameter range was normalized using a logarithmic or linear scale such that the baseline value was mapped to a value of 0 and the upper and lower bounds of the range were mapped to 1 and −1, respectively. See Section 2.1 for details of the computation of linear fit slopes, selected to define sensitivity indices.

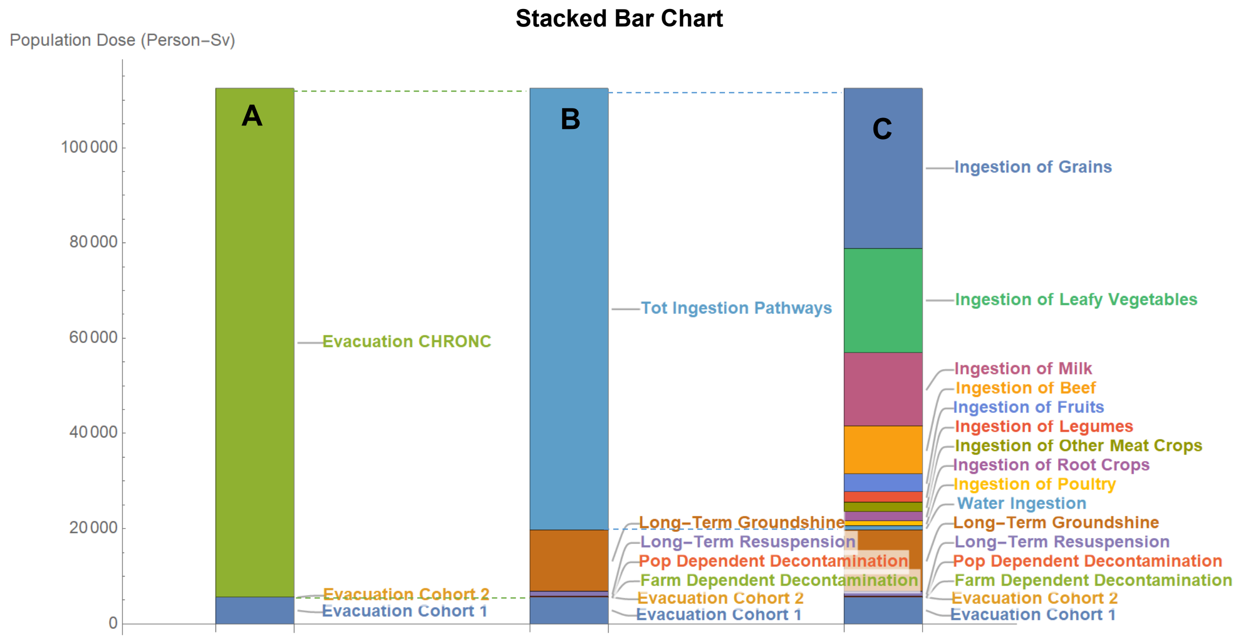
As explained in Section 2.1, the total population dose and economic cost, over a radius spanning 1609.34 km from the fallout epicenter, were selected as the MACCS consequences. Other consequence metrics are available in the output file tbl_outStat.txt, such as extent of condemned land, early-fatality radius, and number of evacuated individuals. A total of 376 outputs are available in the file tbl_outStat.txt. Only four different types of outputs were considered in preparing the sensitivity plots in Section 2.

The population dose (labeled “Evacuation CHRONC L-ICRP60ED [0.,1609.34](km)” in tbl_outStat.txt) includes contributions from the early phase, the chronic phase, and from external exposure and ingestion. Figure 3-1 provides a visualization of the different contributors to the population dose. The stacked bar labeled A in the top plot separates the early phase dose to individual and evacuation cohorts and the chronic dose. The dominant proportion of the population dose is the chronic dose, after the early phase. The stacked bar labeled B indicates that the dominant components of the chronic dose are long-term external exposure (groundshine) and the ingestion dose (food and water ingestion). The stacked bar labeled C indicates that water ingestion is a minor component of the ingestion pathway. The ingestion pathway is overwhelmed by the contribution of dose from food ingestion. The top dose contributors to the food pathway are ingestion of grains and ingestion of leafy vegetables, in the baseline case.

The lower bar chart in Figure 3-1 is a standard rotated bar chart comparing the magnitude of all of the contributors to the population dose on a logarithmic scale. The food ingestion dose (related to outputs of the COMIDA2 model) is a dominant component of the total dose in the baseline case. It should be noted that the population also depends on other factors such as the source term and user-defined individual dose food intake dose limits assumed to trigger interdiction actions.

In the MACCS model, interdiction actions (e.g., farmland interdiction, farmland condemnation, and farmland decontamination) are implemented to control the population dose. Those actions may help in reducing the population dose, but they incur an economic cost. The interdiction actions are triggered when specific dose limits are exceeded (limits input in the WinMACCS through the variables DOSEMILK, DOSEOTHER, and DOSELONG). In the case of exceedance of the DOSELONG limits, all farm products are impounded, without any selective screening (such as removing only the most contaminated food types). Different metrics are available in the

tbl_outStat.txt to quantify the extent of interdiction actions, such as costs and farm disposal areas.



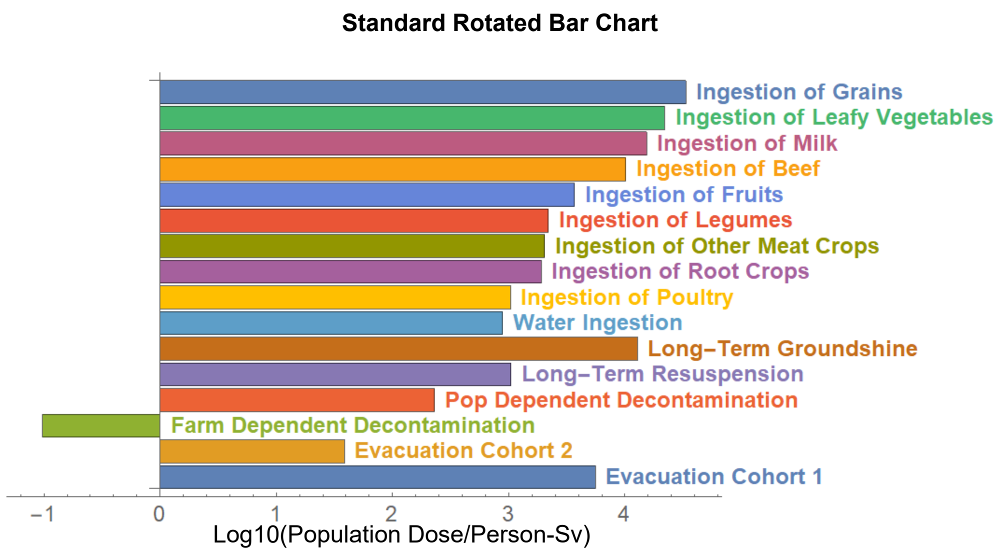
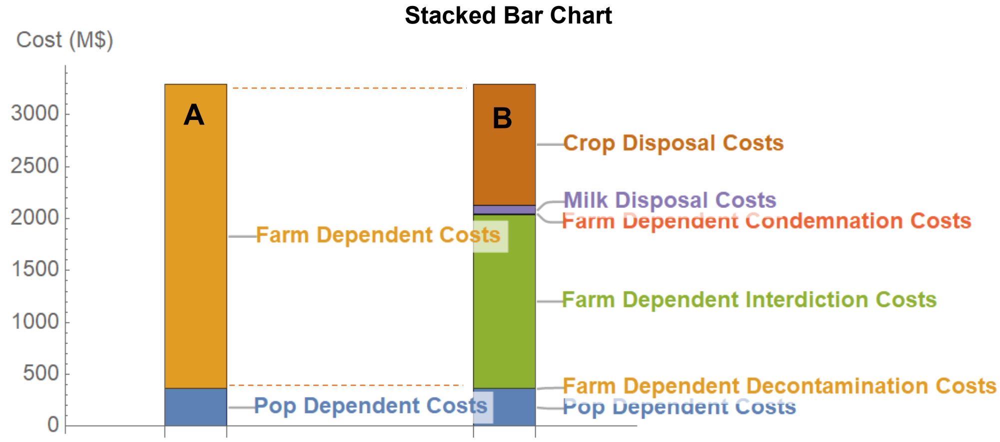


Figure 3-1. Stacked bar chart: contribution of different pathways to the total population dose (evacuation and chronic dose over a 1,609.34-km radius). The stacks A, B, and C correspond to the same total population dose, reflecting different groups of dose contributors (i.e., the contributors to the chronic evacuation dose in Stack A are itemized in Stack B; the contributors to the ingestion dose in Stack B are itemized in Stack C). Standard bar chart: comparison of the magnitude of the contributors to the population dose on a logarithmic scale.

The total economic cost (with the label “Evacuation CHRONC [0.,1,609.34](km)” in tbl_outStat.txt) includes contributions from population costs and farm dependent costs. Figure 3-2 presents the different contributions of the total economic cost. The stacked bar labeled A in the top bar chart indicates that the farm dependent costs dominate the total cost in the baseline case, taking into account that the relative cost contribution is also a function of the source term and inputs to the economic loss model. The stacked bar with label B indicates that the dominant components of the farm dependent costs are crop disposal, farm interdiction, and milk disposal. The farm dependent costs are associated with outputs of the COMIDA2 model. The lower plot in Figure 3-2 is a standard bar chart, comparing the magnitude of the cost of different contributors to the total economic cost. The bar chart indicates that farm-dependent interdiction costs and crop disposal costs are dominant components of the total economic cost.



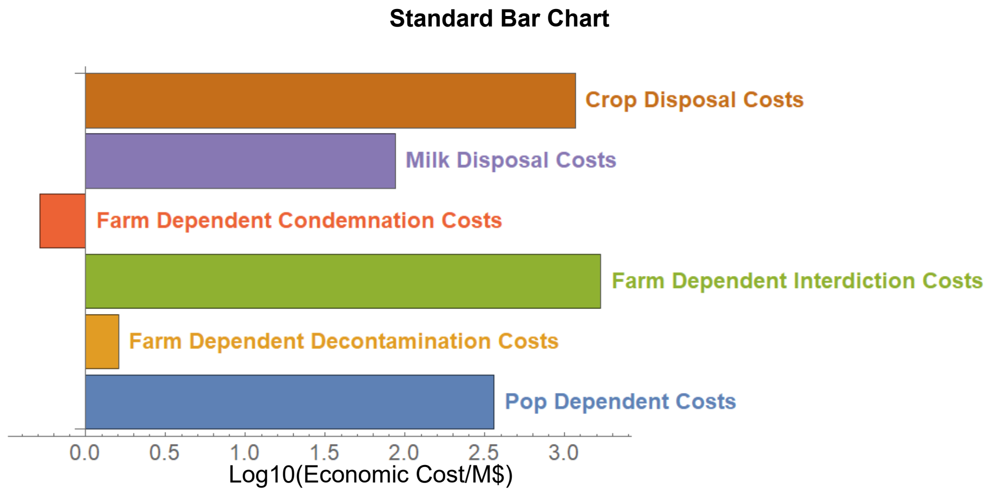


Figure 3-2. Stacked bar chart: different contributors to the total economic cost (over a 1,609.34-km radius). The contributors to the farm dependent costs in Stack A in the top bar chart are itemized in the Stack B. Standard bar chart: comparison of the magnitude of the contributors to the economic cost on a logarithmic scale.

The bar charts in Figure 3-1 and Figure 3-2 highlight the importance of the COMIDA2 model to Level III probabilistic risk assessments.

A total of 133 COMIDA2 inputs were examined. Sensitivity indices (slopes of linear-log or linear-linear fits) were computed for each of those inputs based on population dose or economic cost outputs. The cumulative distributions of the sensitivity indices are displayed in Figure 3-3. Visual outliers, that is, inputs that have relatively strong effects on the population dose or economic cost, are highlighted with triangles. A total of seven visual outliers were identified in both cases. For reference, a sensitivity index equal to +1 corresponds to an input that caused a change of approximately 100 percent in the output (population dose or economic cost) when the highest value of the domain (typically baseline×10) was input.

Figure 3-4 includes tornado bar charts identifying the COMIDA2 inputs with the top 25 sensitivity indices based on population dose and economic cost MACCS outputs. Table 3-1 is the sorted list of the top 10 parameters to the population dose and the top 10 parameters to the economic cost. (Duplicates were removed, resulting in a list with 17 entries.)

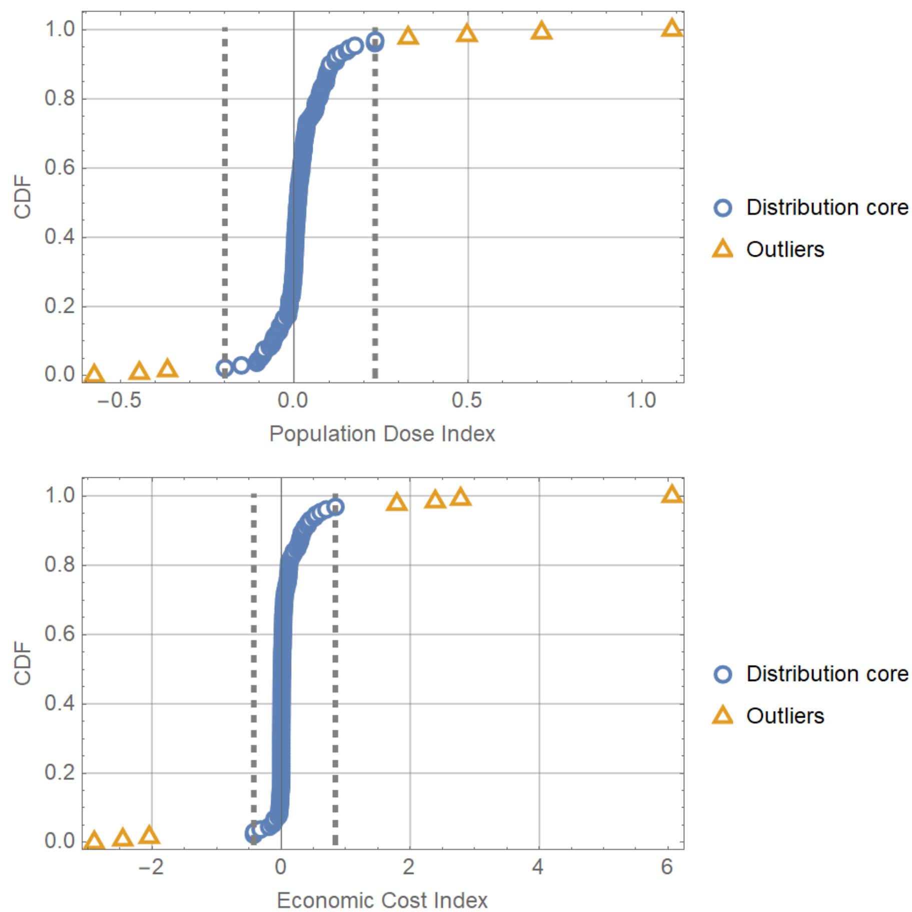


Figure 3-3. Cumulative distribution of the sensitivity indices based on the population dose and the economic cost. Each plot includes 133 indices (corresponding to 133 inputs of the COMIDA2 model)

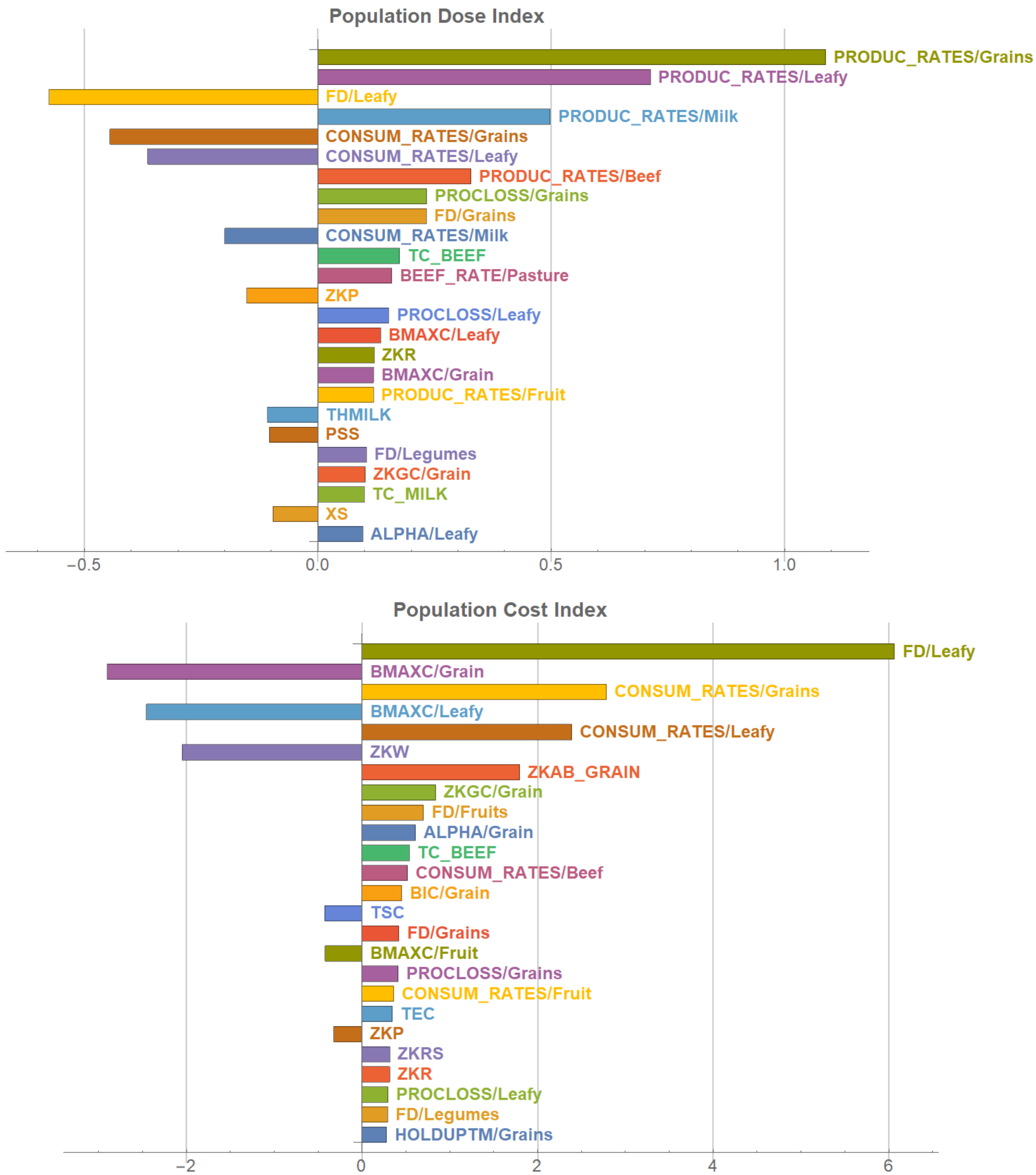


Figure 3-4. Top 25 COMIDA2 inputs ranked by the sensitivity index for dose and cost calculations

Table 3-1. Parameters with the highest sensitivity indices.

Variable	Description	Dose index	Cost index	Report Section
ALPHA/Grains	Foliar interception constant	0.08	0.61	Section 2.3.4
BMAXC/Grains	Max areal biomass	0.12	-2.90	Section 2.3.2
BMAXC/Leafy	Max areal biomass	0.13	-2.46	Section 2.3.2
CONSUM_RATES/Grains	Consumption rates	-0.45	2.78	Section 2.7.4
CONSUM_RATES/Leafy	Consumption rates	-0.36	2.39	Section 2.7.4
CONSUM_RATES/Milk	Consumption rates	-0.20	0.10	Section 2.7.4
FD/Fruits	Dry to wet mass ratio	0.06	0.70	Section 2.6.1
FD/Grains	Dry to wet mass ratio	0.23	0.42	Section 2.6.1
FD/Leafy	Dry to wet mass ratio	-0.58	6.06	Section 2.6.1
PROCLOSS/Grains	Contamination reduction factor	0.23	0.41	Section 2.7.2
PRODUC_RATES/Beef	Production rates	0.33	0	Section 2.7.4
PRODUC_RATES/Grains	Production rates	1.09	0	Section 2.7.4
PRODUC_RATES/Leafy	Production rates	0.71	0	Section 2.7.4
PRODUC_RATES/Milk	Production rates	0.50	0	Section 2.7.4
ZKAB_GRAIN	Foliar absorption rate constant	-0.01	1.79	Section 2.4.6
ZKGC/Grains	Plant growth rate	0.10	0.84	Section 2.3.3
ZKW	Weathering rate	-0.09	-2.05	Section 2.4.5

Most of the entries in Table 3-1 were discussed in Sections 2.6 and Section 2.7. Those inputs are linearly related to the individual dose (e.g., consumption rates, dry to wet mass ratio, and PROCLOSS) or to the population dose (e.g., production rates). The maximal areal biomass (BMAX) is (mostly) inversely proportional to food concentrations and to the individual dose. Parameters that do not follow the linear dependence or inversely proportional dependence are the foliar interception constant (ALPHA), the foliar absorption rate constant (ZKAB), the plant growth rate (ZKG), and the weathering rate (ZKW), all of which have a relatively significant influence on the economic cost.

The sensitivity analysis highlights two crops: grains and leafy vegetables. The grains are relatively dry foodstuffs [i.e., high dry to wet mass ratio (FD)], which makes grains have relatively high radioactivity concentrations. The foliar absorption rate constant (ZKAB), the translocation factor, and the plant growth rate (ZKG) of grains are relatively low. The individual dose consequences of the grains could be higher if the ZKAB or ZKG were higher (increasing uptake of radioactivity in the grains with higher ZKAB or ZKG) and those input parameters thus become highlighted by the sensitivity analysis. Due to data uncertainty, in the baseline case high values of the translocation constant and the foliar absorption rate constant (ZKAB) for leafy vegetables were assumed. This assumption causes high assimilation in plant tissues of the initial radioactivity deposited on plant surfaces by the fallout accident. BMAX(leafy) is relatively low, and the assumption of high ZKAB combined with low values of the BMAX causes leafy vegetables to have relatively high radionuclide concentrations compared to the other crops. Consumption of grains and leafy vegetables dominate the population ingestion dose in the baseline case (Figure 3-1). Milk is a product highlighted in Table 3-1; the ingestion rate (CONSUM_RATES) of this food product is relatively high.

The user is cautioned against general conclusions based on this report's sensitivity analysis, which depends on the selection of the baseline case. Although the input values for the baseline case were carefully selected, it is recognized that further refinements are possible, such as less extreme selection of the translocation constant and foliar absorption rate constant (ZKAB) for leafy vegetables. Selection of a different baseline case would change the conclusions of the sensitivity analysis.

Numerous COMIDA2 inputs were exercised beyond reasonable ranges of physical variability, with the goal to examine the mathematical structure of COMIDA2 and to identify important model assumptions and approximations. Accounting for the range of the physical variability in the COMIDA2 input parameters and for the physical correlation of some variables [e.g., correlation between the weathering (ZKW) and the foliar absorption rate (ZKAB); between BSTAND and BMAX; between cesium soil absorption (ZKAD) and desorption (ZKDE); between soil percolation (ZKP) and leach (ZKL); between the human consumption of all foodstuffs; and between consumption and production rates] would change the results of the sensitivity analysis. Executing a global sensitivity-uncertainty analysis in Monte Carlo mode, with simultaneous variation of the inputs, would yield additional information on relevant uncertainties that should be propagated in general and site-specific analyses. The local sensitivity analysis presented in this report has identified several inputs that require special attention. Over the general two-order-of-magnitude variation explored, the sensitivity analysis indicates that most COMIDA2 inputs have a small to moderate effect on the population dose and economic cost (e.g., less than 50 percent change). Only a few parameters (fewer than 20) have a relatively more important effect on dose and cost estimates. Those with more important effects mostly correspond to inputs that are linearly or inversely proportional to individual doses or population doses.

One aspect of the COMIDA2 model that differs from other food intake dose modes is the consideration of farming seasons and the date of the fallout accident. Farming dates are required inputs of the COMIDA2 model (e.g., start of the crop growing season, harvesting date, and start of livestock grazing season). In the MACCS-COMIDA2 implementation, up to nine fallout accident dates can be considered and spread over the year to examine different scenarios, and average statistics of the different accident dates are output by the MACCS code. Dates defining the duration of the crop growing season [i.e., start of the growing season (TSC) and harvesting date (TEC)] have a relatively more influential effect than other agricultural dates on the population dose and economic cost MACCS outputs. However, the effect of varying the agricultural dates alone is secondary to the effect of assuming a fallout event occurs near the beginning or near the end of a crop growing season. If considered that pasture grows in a short period and plateaus after approximately 30 days after the start of the pasture growing season date (in consistency with the plant biology), this approximation may underestimate the radioactivity intake by beef cattle and dairy cows from pasture (because of the narrow time window assumed for radionuclide transfer from root soil to the plant tissues limited to approximately 30 days). To address this underestimation (Section 2.3.3), a modification of the pasture growth rate was proposed based on the duration of the grazing season instead of on the plant growing cycle. This approximation was not incorporated in the baseline case; instead, the baseline case considered the approximately 30-day pasture maturity cycle.

Non-intuitive increasing trends in population dose and cost with were identified when some holdup times (delay from food production to consumption) increased. Those increasing trends were associated with the use of the holdup time to allocate the consumption of the food produced between the current and the next accident year (years measured with respect to the fallout event). Those trends are considered artificial and possibly unintended, and it is recommended that the use of the holdup time to allocate the food consumption between

accident years is disabled, or a logical (true/false) input is added to enable/disable the inclusion of holdup in the equation used to compute the allocation. By examining contents of the ComidaN.lst files it was identified that crop foods are consumed during a period up to 365 days after the harvest (with radionuclide concentrations undergoing decay). In updates to the COMIDA2 model it is recommended that decay of crop concentrations is defined by the holdup time, and not beyond, to avoid potentially underestimating radioactivity intake (especially of short-lived radionuclides) and dose and cost consequences.

The baseline inputs are regarded as reasonable inputs for generic consequence assessments. Site-specific inputs could be enhanced relative to the baseline inputs for individual food consumption rates and food production rates of locally consumed foodstuffs. However, acquiring this information can be very labor intensive, requiring of local surveys. Inputs could be considered uncertain (i.e., defined through distribution functions to be sampled in the MACCS code), but care should be exercised in avoiding defining average total individual food consumption rates beyond reasonable levels. For example, an average annual food consumption rate is on the order of 500 kg; the COMIDA2 model only tracks average individuals. Chanin et al. (1998) recommend developing inputs for consumption and production rates that are balanced. If not balanced, the MACCS model outputs population dose estimates outside the modeled grid, which should be carefully interpreted.

Additional site-specificity could be incorporated in the definition of the *other animal* type. In the baseline case, it was assumed that the other animal type is an egg-laying hen, given that eggs are common in people's diets, can be locally produced, and could carry a higher radioactivity concentration than other protein products. The *other animal* could be used to simulate pork, when important to the local diet; however, general sources of information for pork products are more limited than for eggs. Finally, another input that could incorporate additional site-specificity is the diet of dairy cows. In the baseline case, it was assumed that dairy cows partially feed on pasture (which would cause contamination of milk from surface fallout). However, it is common practice to keep dairy cows fed with stored hay and other feeds obtained from non-local sources, which could reduce the exposure of cows to contamination.

4 REFERENCES

Abbott, M.L. and A.S. Rood. “COMIDA: A Radionuclide Food Chain Model for Acute Fallout Deposition.” *Health Physics*. Vol. 66. pp. 17–29. 1994.

Abbott, M.L. and A.S. Rood. “COMIDA: A Radionuclide Food Chain Model for Acute Fallout Deposition.” EGG-GEO-10367, Rev. 0. PB2008-108924. Idaho Falls, Idaho: Idaho National Engineering Laboratory. November 1993.

Abbott, M.L. and D.R. Wenzel. “Dose Calculations for Routine Airborne Releases of ITER Activation Products.” EGG-EEL-11108, Rev. 0. Idaho Falls, Idaho: Idaho National Engineering Laboratory. 1994.

Anspaugh, L., J. Shinn, P. Phelps, and N. Kennedy. “Resuspension and Redistribution of Plutonium in Soils.” *Health Physics*. Vol. 29. pp. 571–582. 1975.

Assimakopoulos, P.A., K.G. Ioannides, and A.A. Pakou. “The Environmental Behavior of ^{131}I in Northwestern Greece Following the Nuclear Reactor Accident at Chernobyl.” *Health Physics*. Vol. 55. pp. 783–91. 1988.

Baes, C. and R. Sharp. “A Proposal for Estimation of Soil and Leaching Constants for use in Assessment Models.” *Journal of Environmental Quality*. Vol. 12. pp. 17–28. 1983.

Baes, C., R. Sharp, A. Sjoreen, and R. Shor. “A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides through Agriculture.” ORNL–5786. Oak Ridge, Tennessee: Oak Ridge National Laboratory. 1984.

Bechtel SAIC Company. LLC. ANL–MGR–MD–000006, “Agricultural and Environmental Input Parameters for the Biosphere Model.” Rev. 02. Las Vegas, Nevada: Bechtel SAIC Company, LLC. September 2004a.

Bechtel SAIC Company. LLC. ANL–MGR–MD–000007, “Environmental Transport Input Parameters for the Biosphere Model.” Rev. 02. Las Vegas, Nevada: Bechtel SAIC Company, LLC. September 2004b.

Bechtel SAIC Company. LLC. ANL–MGR–MD–000005, “Identification of the Critical Group (Consumption of Locally Produced Food and Tap Water).” Rev 0. Las Vegas, Nevada: Bechtel SAIC Company, LLC. September 2000.

Beyeler, W.E., W.A. Hareland, F.A. Duran, T.J. Brown, E. Kalinina, D.P. Gallegos, and P.A. Davis. NUREG/CR–5512, “Residual Radioactive Contamination from Decommissioning, Parameter Analysis, Draft Report for Comment.” Volume 3. SAND99-2148. ML082460902. Albuquerque, New Mexico: Sandia National Laboratories. October 1999.

Chanin, D., M.L. Young, J. Randall, and K. Jamali. “NUREG/CR–6613, “Code Manual for MACCS2: Volume 1, User’s Guide” and “Volume 2, Preprocessor Codes COMIDA2, FGRDCF, IDCF2.” ML17047A443 and ML17047A444. Washington, DC: U.S. Nuclear Regulatory Commission. 1998.

Dreicer, M., T.E. Hakonson, G.C. White, and F.W. Whicker. “Rainsplash as a Mechanism for Soil Contamination of Plant Surfaces.” *The Radiation Safety Journal–Health Physics*. Vol. 46. pp. 177–187. 1984.

IAEA. “Environmental Change in Post-Closure Safety Assessment of Solid Radioactive Waste Repositories.” IAEA–TECDOC–1799. Vienna, Austria: International Atomic Energy Agency. 2016.

IAEA. “Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments.” Technical Reports Series No. 472. Vienna, Austria: International Atomic Energy Agency. 2010.

IAEA. “Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments.” IAEA–TECDOC–1616. Vienna, Austria: International Atomic Energy Agency. 2009.

IAEA. “Reference Biospheres for Solid Radioactive Waste Disposal.” IAEA-BIOMASS-6. Vienna, Austria: International Atomic Energy Agency. 2003.

IAEA. “Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments.” Technical Reports Series No. 364. Vienna, Austria: International Atomic Energy Agency. 1994.

IAEA. “Modeling of Resuspension, Seasonality and Losses during Food Processing First Report of the VAMP Terrestrial Working Group.” IAEA–TECDOC–647. Vienna, Austria: International Atomic Energy Agency. 1992.

Ishida, J., N. Miyagawa, H. Watanabe, T. Asano, and Y. Kitahara. “Environmental Radioactivity Around Tokai-Works After the Reactor Accident at Chernobyl.” *Journal of Environmental Radioactivity*. Vol. 7, Issue 1. pp. 17–27. 1988. <https://doi.org/10.1016/0265-931X(88)90039-2> (accessed 1 May 2020).

Kennedy, Jr., W.E. and D.L. Strenge. “Residual Radioactive Contamination from Decommissioning, Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent.” NUREG/CR–5512, Volume 1. PNL–7994. Richland, Washington: Pacific Northwest Laboratory. October 1992.

Kirchner, G. “Transport of Iodine and Caesium Via the Grass-Cow-Milk Pathway After the Chernobyl Accident.” *Health Physics*. Vol. 66. pp. 653–665. 1994.

Langham, W.H. “The Biological Implications of the Transuranium Elements for Man.” *Health Physics*. Vol. 22. pp. 943–952. 1972.

LaPlante, P.A., O. Pensado, L. Howard, J.W. Mancillas. “A Biosphere Sensitivity Analysis Using BDOSETM Version 2.0.” NRC ADAMS Accession No. ML110750358. San Antonio, Texas: Center for Nuclear Waste Regulatory Analyses. 2011

Lim, K.M., D.W. Park, H.G. Park, Y.H. Choi, S.D. Choi, and C.M. Lee. “Analysis of the Direct Contamination Pathway of ^{85}Sr, ^{103}Ru and ^{134}Cs in Soybean.” Proceedings of the Korean Nuclear Society Spring Meeting, Cheju, Republic of Korea, May 24–25, 2001.

McFadden, K., N.E. Bixler, L. Eubanks, and R. Haaker. “WinMACCS, a MACCS2 Interface for Calculating Health and Economic Consequences from Accidental Release of Radioactive Materials Into the Atmosphere. User’s Guide and Reference Manual, WinMACCS Version 3.” ML072350221. Washington, DC: U.S. Nuclear Regulatory Commission. August 2007.

Miller, C. and F. Hoffman. “An Examination of the Environmental Half-Time for Radionuclides Deposited on Vegetation.” *Health Physics*. Vol. 45. pp. 731–744. 1983.

Miller, C.W. “An Analysis of Measured Values for the Fraction of a Radioactive Aerosol Intercepted by Vegetation.” *Health Physics*. Vol. 38. pp. 705–712. 1980.

Monte, L. “Analysis of Radiocontamination Data Collected in Italy Following the Chernobyl Accident for the Evaluation of Transfer Parameters of Radionuclides in the Deposition-Vegetation-Cow-Milk Pathway.” *Journal of Environmental Radioactivity*. Vol. 14. pp. 317–329, 1991.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, R. Srinivasan, and J.R. Williams. “Soil and Water Assessment Tool User Manual.” College Station, Texas: Texas Water Resources Institute. 2002.

NRC. NUREG–1925, “Research Activities FY 2018-2020.” ML18071A139. Washington, DC: U.S. Nuclear Regulatory Commission. 2018.

NRC. Regulatory Guide 1.109, “Calculation of Annual Doses to Man From Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance With 10 CFR Part 50, Appendix 1.” ML13350A285. Washington, DC: U.S. Nuclear Regulatory Commission. 1977.

Ohmomo, Y., Y. Muramatsu, S. Uchida, and M. Sumaiya. “Food Chain and Radioactivity–Migration of Iodine-129 to Rice Plant.” Global Environment and Nuclear Energy. Proceedings of the 3rd International Symposium on Advanced Nuclear Energy Research. Vienna. pp. 36–40. 1991.

Pinder, J.E. and D.C. Doswell. “Retention of ^{238}Pu-Bearing Particles by Corn Plants.” *Health Physics*. Vol. 49. pp. 771–776. 1985.

Pinder, J.E., D.C. Adriano, T.G. Ciravolo, A.C. Doswell, and D.M. Yehling. “The Interception and Retention of ^{238}Pu Deposition by Orange Trees.” *Health Physics*. Vol. 52. pp. 707–715. 1987.

PNNL. NUREG/CR–6825, “Literature Review and Assessment of Plant and Animal Transfer Factors Used in Performance Assessment Modeling.” PNNL–14321. Richland, Washington: Pacific Northwest National Laboratory. 2003.

Sheppard, M. and D.H. Thibault. “Default Soil Solid/Liquid Partition Coefficients, Kds, for Four Major Soil Types: A Compendium.” *Health Physics*. Vol. 59. pp. 471–482. 1990.

Shor, R., C. Baes, C. and R.D. Sharp. “Agricultural Production in the United States by County: A Compilation of Information from the 1974 Census of Agriculture for Use in Terrestrial Foodchain Transport and Assessment Models.” ORNL–5768. Oak Ridge, Tennessee: Oak Ridge National Laboratory. 1982.

Smith, G., B. Watkins, R. Little, H. Jones, and A. Mortimer. "Biosphere Modeling and Dose Assessment for Yucca Mountain." EPRI TR-107190. Palo Alto, California: Electric Power Research Institute. 1996.

SNL. "State-of-the-Art Reactor Consequence Analyses Project, Volume 2: Surry Integrated Analysis." ML120260681. Albuquerque, New Mexico: Sandia National Laboratories. January 2012.

SNL. "Biosphere Model Report." MDL–MGR–MD–000001. Rev 02. ML090720287. Las Vegas, Nevada: Sandia National Laboratories. August 2007.

Squire, H.M. and L.J. Middleton. "Behavior of 137^{Cs} in Soils and Pastures–A Long Term Experiment." *Radiation Botany*. Vol. 6. pp. 413–423. 1966.

Sutter, S.L. NUREG/CR–2651, "Accident Generated Particulate Materials and Their Characteristics–A Review of Background Information." PNL-4154. Richland, Washington: Pacific Northwest Laboratory. 1982.

Till, J.E. and H.A. Grogan. "Radiological Risk Assessment and Environmental Analysis." New York, New York: Oxford University Press. 2008.

United States Department of Agriculture (USDA). "National Agricultural Statistics Service Database." 2012. https://www.nass.usda.gov/Publications/AgCensus/2012/#full_report (Accessed date 2 May 2020).

Whicker, F. and T. Kirchner. "PATHWAY: A Dynamic Food-Chain Model to Predict Radionuclide Ingestion After Fallout Deposition." *Health Physics*. Vol. 52. pp. 717–737. 1987.

Yu, C., A.J. Zielen, J.J. Cheng, D.J. LePoire, E. Gnanapragasam, S. Kamboj, J. Arnish, A. Wallo III., W.A. Williams, and H. Peterson. "User's Manual for RESRAD Version 6." ANL/EAD-4. Argonne, Illinois: Argonne National Laboratory. 2001.